

Human Thermal Environments

The Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort, and Performance

Third Edition



Ken Parsons



CRC Press
Taylor & Francis Group

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Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

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Version Date: 20140114

International Standard Book Number-13: 978-1-4665-9600-9 (eBook - PDF)

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Contents

Preface to the Third Edition	xix
Preface to the Second Edition	xxi
Preface to the First Edition	xxiii
Acknowledgements to the Third Edition	xxv
Acknowledgements to the Second Edition	xxvii
Acknowledgements to the First Edition	xxix
Author	xxxi
List of Notations	xxxiii
Chapter 1 Human Thermal Environments	1
Introduction	1
Heat Transfer	3
Conduction	3
Convection	4
Dimensionless Numbers	4
Convective Heat Transfer in Air and Water	8
Evaporation	12
Radiation	14
Basic Parameters	14
Temperature	14
Air Temperature (t_a)	16
Radiant Temperature	16
Mean Radiant Temperature (t_r)	17
Plane Radiant Temperature (t_{pr})	17
Solar Radiation	19
Quantity: Solar Radiation Level	19
Quality: Spectral Content of Solar Radiation	19
Solar Radiation and the Human Body	21
Direct Solar Radiation	21
Diffuse Solar Radiation	22
Temperature Charts and Scales	22
Practical Working Scales ($^{\circ}\text{C}$, $^{\circ}\text{F}$)	23
Absolute Temperature Scale (K)	24
Air Velocity (v)	24
Humidity	25
Heat Transfer for a Cylinder	27
Conduction in Cylinders	27
Multiple Concentric Cylinders	29
Role of Heat Transfer Theory in the Assessment of Human Thermal Environments	32

Chapter 2	The Human Heat Balance Equation and the Thermal Audit	33
	The Heat Balance Equation for the Human Body	33
	The Conceptual Equation	33
	Units	34
	Body Surface Area	34
	The Practical Heat Balance Equation	35
	Heat Production within the Body ($M - W$)	36
	Sensible Heat Loss ($R + C$)	36
	Evaporative Heat Loss from the Skin (E_{sk})	38
	Heat Loss from Respiration ($C_{res} + E_{res}$)	39
	The Thermal Audit	40
	Basic Parameters	40
	Simple Calculations	40
	Heat Transfer Coefficients	41
	Calculation of Components of the Heat Balance Equation	42
	Heat Balance and Clothing Ventilation	44
	Heat Balance and Solar Load	45
	Expert Estimation of the Thermal Audit	46
	Analysis	47
	Metabolic Heat Production	47
	Dry Heat Transfer	47
	Heat Loss by Evaporation at the Skin	47
	Heat Transfer by Respiration	47
	Assessment of Environments Using the Thermal Audit	48
	Summary	57
Chapter 3	Human Thermal Physiology and Thermoregulation	59
	Introduction	59
	Thermal Properties of the Human Body	60
	Effects of Blood Flow	60
	Human Thermoregulation	64
	Neuronal Models	68
	Hierarchy of Systems	69
	Physiological Responses	69
	Thermosensors	69
	Central Components	70
	Vasodilation, Vasoconstriction and Direction of Blood Flow	70
	Piloerection	71
	Heat Production by Shivering	71
	Sweating	72
	Behavioural Thermoregulation	73
	Body Temperature	75
	Core Temperature	76
	Shell Temperature	76

Mean Body Temperature	76
Comfort as the Regulated Variable	77
Chapter 4 Psychological Responses and Human Behaviour.....	79
Introduction	79
Psychological Models.....	81
Thermal Sensation.....	83
Thermoreception	85
Nerve Endings	85
Psychophysics.....	90
Whole-Body Responses.....	91
Semantics, Psychological Models and Multidimensional Scaling	92
Scales of Warmth Sensation	93
Mood, Aggression, Depression and Other Psychological Reactions	94
Behavioural Responses.....	96
Threat, Expectancy and Pleasure	98
Discussion.....	99
Chapter 5 Measurement Methods and Assessment Techniques	101
Introduction	101
Air Temperature (t_a).....	102
Mean Radiant Temperature (t_r).....	104
Plane Radiant Temperature and Radiant Temperature	
Asymmetry	107
Solar Radiation	109
Air Velocity (v)	109
Humidity.....	113
Equilibrium Temperatures for Dry and Wet Sensors	114
Measuring Kits and Composite Instruments.....	117
‘Admiralty Box’	117
Indoor Climate Analyser	118
Other Instruments.....	119
Direct Measures of Heat Transfer	119
Thermal Manikins.....	119
Measurement of Physiological Response	120
Skin Temperature	120
Measurement of Internal Body Temperature	122
Tympanic Temperature.....	123
Aural Temperature.....	123
Forehead Temperature	124
Oral Temperature.....	124
Oesophageal Temperature	124
Subclavian Temperature	124
Intra-Abdominal Temperature	125

	Rectal Temperature.....	125
	Urine Temperature.....	125
	Transcutaneous Deep Body Temperature.....	125
	Preferred Measure of Internal Body Temperature	126
	Measurement of Thermal Effects on Heart Rate	126
	Measurement of Body Mass Loss	127
	Personal Monitoring Systems.....	128
	Specification of Physiological Monitoring Instruments	128
	Measurement of Psychological Responses.....	129
	Subjective Measures	129
	Behavioural and Observational Measures.....	133
	Thermal Index: An Assessment Technique	135
	Rational Indices.....	135
	Empirical Indices	136
	Direct Indices	136
Chapter 6	Dehydration and Water Requirements	139
	Introduction	139
	Body Water.....	139
	Control of Body Water	141
	Dehydration Measures.....	142
	Measures in Sweat.....	143
	Measures in Blood.....	143
	Measures in Urine.....	143
	Skin Condition.....	147
	Thirst	147
	Bioelectrical Impedance Analysis (BIA)	150
	Dehydration Limits	151
	Practical Recommendations for Drinking	153
	Drinking Too Much.....	158
Chapter 7	Thermal Models	161
	Introduction	161
	Thermal Models	161
	Empirical Models.....	162
	Givoni/Goldman Model.....	162
	Calculation of M_{net}	162
	Environmental Heat Load ($R + C$).....	163
	Required Evaporative Cooling.....	163
	Evaporative Capacity	164
	Predictive Formulae.....	164
	Time Pattern at Rest under Heat Stress Conditions.....	165
	Time Pattern of Elevation during Work.....	165

Recovery Time Pattern of Rectal Temperature after Work....	165
Validation of the Predictive Formulae.....	165
Database Models	166
Rational Thermal Models.....	167
Stolwijk and Hardy 25-Node Model.....	167
Pierce Two-Node Model.....	168
Wissler Model.....	172
Werner Model.....	172
The Fiala Model	174
The UTCI–Fiala Model.....	175
The ‘ISO Model’	177
Other Models	178
Do Models Work?.....	180
Hybrid Models.....	184
Computer-Aided Design.....	185
Chapter 8 Metabolic Heat Production.....	187
Introduction	187
Where Does the Heat Come from?	187
Units.....	189
Estimation of Metabolic Heat Production.....	189
Calorimetry	189
Indirect Calorimetry.....	190
Collection and Analysis of Expired Air.....	193
The Doubly Labelled Water (DLW) Method	194
External Work (<i>W</i>)	195
The Use of Tables and Databases.....	195
General Description of Work	195
General Description by Occupation	196
Summation Method.....	196
Estimation for Basic Activities.....	197
Estimation for Component Occupational Tables.....	197
Empirical Models	198
Heart Rate Method	198
Subjective Methods	200
Metabolic Rate, VO_{2max} , VO_{2peak} and the O_2 Disassociation Curve	200
Effects of Temperature and Thermoregulation	201
Combination of Activities.....	202
Task and Activity Analysis Methods.....	202
Paced and Non-paced Tasks	203
Accuracy of Methods	203
Special Populations: Children, People with Physical Disabilities and People Wearing Protective Clothing and Equipment.....	204

Chapter 9	The Thermal Properties of Clothing	211
	Introduction	211
	A Simple Clothing Model	212
	Heat Transfer from Body to Skin	212
	Intrinsic Clothing Insulation, I_{cl}	213
	Thermal Resistance of the Environment: Air 'Layer' (I_a).....	213
	'Total' Insulation (I_t) and Effective Insulation (I_{cle}).....	214
	Burton Thermal Efficiency Factor (F_{cl}).....	215
	Method of Determining Dry Thermal Insulation of Clothing	215
	The Two-Parameter Model.....	219
	Intrinsic Resistance of Clothing to Vapour Transfer (I_{ecl}).....	220
	Resistance of the Environment to Vapour Transfer from Clothing (I_{ea}).....	220
	Vapour Permeability Indices	222
	Woodcock 'Moisture Permeability Index' (i_m).....	222
	Permeation Efficiency Factor (F_{pcl})	223
	Modification of the Two-Parameter Model: Wicking	226
	Ventilation in Clothing	227
	Clothing Ventilation: Empirical Methods	229
	More Complex Clothing Models and the Three-Parameter Model.....	232
	Summation of Clothing Insulation Values and Parallel versus Series Methods	233
	Psychrometrics and Clothing Properties	234
Chapter 10	Testing and Developing Clothing	235
	Introduction	235
	Determination of the Thermal Properties of Clothing.....	235
	Determination of Thermal Properties of Clothing Using ISO 9920 (2007).....	235
	Thermal Manikins.....	235
	Level 1: Biophysical Analysis, Textiles	239
	Level 2: Manikin Tests	241
	Higher-Level Tests.....	245
	User Tests and Trials	246
	Performance Tests	246
	Performance Trials	249
	The Design of Functional Clothing.....	250
	Survival Suits.....	252
	Active and Smart Clothing	253
	Clothing Specification and the Window of Application	255

Chapter 11 Thermal Comfort 257

 Introduction 257

 Whole-Body Thermal Comfort 258

 Historical Perspective 258

 Effective Temperature 259

 Resultant Temperature 260

 Equivalent Temperature 261

 Kansas Laboratory Trials 263

 Fanger (1970) 264

 The Comfort Equation 264

 Heat Balance 265

 Sweat Rate and Skin Temperature for Comfort 265

 Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) 268

 Comfort Studies of Gagge et al.: ET*, PMV*, SET, the Two-Node Model and Enthalpy 270

 PMV, PMV*, ET* and Enthalpy 276

 Thermal Models and Thermal Comfort 277

 Behavioural Thermoregulation, Thermal Comfort and the Adaptive Model 277

 Adaptive Modelling and the ASHRAE Studies 278

 British Studies and Adaptive Models 280

 Equivalent Clothing Index (I_{EQUIV}) 281

I_{EQUIV} and the Comfort Temperature Range 284

 Local Thermal Discomfort 284

 Draughts 285

 Asymmetric Thermal Radiation 285

 Vertical Air Temperature Differences 286

 Local Discomfort Caused by Surface Contact 287

Chapter 12 Thermal Comfort for Special Environments 291

 Thermal Comfort in Special Environments 291

 Personal Control Environments 291

 Displacement Ventilation and Chilled Ceiling Environments 293

 Thermal Comfort in Vehicles 294

 Thermal Comfort on Train Journeys 300

 Outdoor Thermal Comfort 303

 Other Special Environments 304

Chapter 13 Thermal Comfort for Special Populations 307

 Introduction 307

 Do Requirements for Comfort Apply Universally? 307

National Geographic Location	308
Effects of Age	309
Effects of Gender	311
Effects of Acclimatisation State on Thermal Comfort	
Requirements	312
Other Factors	313
People with Disabilities	313
The Loughborough Studies into Thermal Comfort	
Requirements for People with Physical Disabilities	315
Loughborough Field Studies	316
Loughborough Laboratory Studies	319
Physical Disabilities and the Adaptive Model	320
Babies, Children, the Sick and the Pregnant	320
Chapter 14 Heat Stress	323
Introduction	323
Physiological Responses to Heat	325
Heat Disorders	326
Heat Stress Indices	331
Introduction	331
Rational Indices	332
Heat Stress Index (HSI)	332
Index of Thermal Stress (ITS)	332
Required Sweat Rate (SW_{req})	334
Predicted Heat Strain (PHS)	335
Determination of the Duration Limited Exposure (DLE)	340
Other Rational Models	341
Empirical Indices	341
Effective Temperature and Corrected Effective Temperature ...	341
Predicted Four-Hour Sweat Rate (P4SR)	342
Heart Rate Prediction	342
Direct Heat Stress Indices	345
Wet Bulb Globe Temperature (WBGT) Index	345
Physiological Heat Exposure Limit (PHEL)	346
Wet Globe Temperature (WGT) Index	347
Oxford Index (WD)	347
Acclimatisation	347
Working Practices for Hot Environments	350
Chapter 15 Cold Stress	355
Introduction	355
Physiological Responses to Cold	355
Psychological Response to Cold	359
Cold Injury and Illness	359
Cold Stress Indices	361

Wind Chill Index (WCI) 361

Equivalent Still Air Temperature (ESAT)..... 364

Equivalent Shade Temperature (*EST*) and Still Shade
Temperature (*SST*)..... 366

 Required Clothing Insulation (IREQ) Index 367

New Wind Chill Index 372

Wind Chill and Convective Heat Transfer 375

Acclimatisation to Cold 376

Working Practices for Cold Environments 378

 Guidance for Evaluation and Control 378

 General..... 378

 Manual Dexterity 378

 Contact Injury 378

 Protective Clothing and Protective Practices 379

 Workplace Recommendations 379

Do the Workers Have to Be Exposed to the Cold?..... 380

Selection of Workers for Cold Work..... 380

Screening 381

System of Reporting 381

Advice..... 381

Case Study of Cold Work in a Hospital ‘Plating Area’ 382

 Background..... 382

 The Project 383

 Method..... 383

 Objective Assessment..... 384

 Subjective Assessment..... 384

 Summary of Recommendations 384

 Clothing Dynamics and Work in the Cold 385

Chapter 16 Thermal Environments and Human Performance 387

Introduction 387

Early Studies: Factory Output and Accidents 389

 Performance in Heat..... 390

 Effects of Heat on Cognitive Performance..... 390

 Effects of Heat on Manual Performance 393

Performance in Moderate Environments 394

 Effects of Moderate Environments on Cognitive Performance 394

 Effects of Moderate Environments on Manual Performance..... 395

Performance in Cold 395

 Effects of Cold Environments on Cognitive Performance 395

 Effects of Cold Environments on Manual Performance 396

 Human Performance in Transient Conditions 397

 Distraction Revisited 397

Performance Models and Indices 399

A Standard Environmental Approach	399
Individual Control and Other Issues.....	399
Reductionist Approach	400
Underlying Models: Explanations and Factors.....	402
Arousal	402
Physiological (Body Temperature)	403
Distraction	403
Perceived Control.....	403
A Rational Performance Model.....	403
Productivity	404
Motivation.....	405
Level of Skill	405
Summary Models	405
Environmental Design for Productivity	406
Chapter 17 Human Skin Contact with Hot, Moderate and Cold Surfaces	409
Introduction	409
Skin Contact with a Hot Surface: Analysis of the Event.....	410
Human Skin.....	410
Skin Reaction to Heating.....	411
Thermoregulatory Response.....	411
Pain	411
Skin Burns	412
Solid Surfaces	413
Analysis of Contact between Skin and a Hot Solid Surface	414
Review of Investigations into Human Skin	
Contact with Hot Surfaces.....	415
Empirical Methods	415
Use of Animal Skin	415
Human Skin.....	419
Scalding.....	422
Mathematical Models of Heat Transfer.....	422
Simple Models	422
Comprehensive Models	426
Physical Models.....	426
The Thermesthesiometer	426
Siekmann	427
Other Physical Models.....	428
Databases, Standards and Limits	428
British Standards	429
European Standards.....	431
International Standards.....	432
Human Data Revisited.....	434
Classification of Skin Damage	436

Prediction of Skin Reaction..... 436
 Contact between Skin and a Hot Surface 437
 Skin Condition 437
A Simple Practical Model 437
Practical Example..... 438
 Procedure for Calculating Equivalent Contact
 Temperature (T_{ceq})..... 438
Surfaces of Moderate Temperature 440
Cold Surfaces 442

Chapter 18 International Standards 445
Introduction 445
ISO Standards..... 445
 ISO 7243: Hot Environments – Estimation of the Heat Stress
 on Working Man, Based on the WBGT Index 448
 Revision of ISO 7243..... 450
 ISO 7933: Ergonomics of the Thermal Environment –
 Analytical Determination and Interpretation of Heat Stress
 Using Calculation of Predicted Heat Strain 452
 Interpretation of Analysis for the Predicted Heat Strain
 Model..... 457
 Determination of Predicted Values 458
 Determination of the Allowable Exposure Duration (DLE) .. 459
 Revision of ISO 7933..... 460
 ISO 7730: Ergonomics of the Thermal Environment –
 Analytical Determination and Interpretation of Thermal
 Comfort Using Calculation of the PMV and PPD Indices and
 Local Thermal Comfort Criteria 460
 Revision of ISO 7730..... 462
 ISO Working Document on Working Practices for Moderate
 Thermal Environments..... 463
 ISO 7726: Ergonomics of the Thermal Environment –
 Instruments and Methods for Measuring Physical Quantities 463
 ISO 8996: Ergonomics of the Thermal Environment –
 Determination of Metabolic Rate..... 464
 ISO 9886: Ergonomics – Evaluation of Thermal Strain by
 Physiological Measurements 466
 ISO 9920: Ergonomics of the Thermal
 Environment – Estimation of Thermal Insulation and
 Water Vapour Resistance of a Clothing Ensemble..... 467
 ISO 11079: Ergonomics of the Thermal Environment –
 Determination and Interpretation of Cold Stress When Using
 Required Clothing Insulation (IREQ) and Local Cooling
 Effects..... 471
 Revision of ISO 11079 473

ISO 15743: Ergonomics of the Thermal Environment – Cold Workplaces – Risk Assessment and Management	474
ISO 10551: Ergonomics of the Thermal Environment – Assessment of the Influence of the Thermal Environment Using Subjective Judgement Scales.....	474
Revision of ISO 10551	475
ISO 11399: Ergonomics of the Thermal Environment – Principles and Application of Relevant International Standards	475
Revision of ISO 11399	475
ISO 12894: Ergonomics of the Thermal Environment – Medical Supervision of Individuals Exposed to Extreme Hot or Cold Environments.....	475
ISO 13731: Ergonomics of the Thermal Environment – Vocabulary and Symbols.....	478
ISO 13732: Ergonomics of the Thermal Environment – Method for the Assessment of Human Responses to Contact with Hot, Moderate or Cold Surfaces.....	478
ISO 13732-1: Ergonomics of the Thermal Environment – Methods for the Assessment of Human Responses to Contact with Surfaces – Part 1: Hot Surfaces	480
ISO TS 13732-2: Ergonomics of the Thermal Environments – Methods for the Assessment of Human Responses to Contact with Surfaces – Part 2: Human Contact with Surfaces at Moderate Temperature	481
ISO 13732-3: Ergonomics of the Thermal Environment – Methods for the Assessment of Human Responses to Contact with Surfaces – Part 3: Cold Surfaces.....	481
ISO 14505: Ergonomics of the Thermal Environment – Evaluation of Thermal Environments in Vehicles, Parts 1–4	482
ISO TS 14505-1: Ergonomics of the Thermal Environment – Evaluation of Thermal Environments in Vehicles – Part 1: Principles and Methods for Assessment of Thermal Stress.....	482
ISO 14505-2: Ergonomics of the Thermal Environment – Evaluation of Thermal Environments in Vehicles – Part 2: Determination of Equivalent Temperature	482
ISO 14505-3: Ergonomics of the Thermal Environment – Evaluation of Thermal Environments in Vehicles – Part 3: Evaluation of Thermal Comfort Using Human Subjects.....	483
ISO 14505-4: Ergonomics of the Thermal Environment – Evaluation of Thermal Environments in Vehicles – Part 4: Determination of the Equivalent Temperature by Means of a Numerical Manikin	483
ISO 15265: Ergonomics of the Thermal Environment – Risk Assessment Strategy for the Prevention of Stress or Discomfort in Thermal Working Conditions	484

- ISO 28802: Ergonomics of the Physical Environment –
Assessment of Environments by Means of an Environmental
Survey Involving Physical Measurements of the Environment
and Subjective Responses of People..... 484
- ISO 28803: Ergonomics of the Physical Environment –
Application of International Standards to People with
Special Requirements..... 485
- ISO DTS 16418: Ergonomics of the Thermal Environment –
Mathematical Model for Predicting and Evaluating the
Dynamic Human Physiological Responses to the Thermal
Environments..... 485
- ISO 15742: Guidance on the Determination of the Combined
Effects of Environmental Components on Human Health,
Comfort and Performance 486
- Standards in the United States 486
 - American Society of Heating, Refrigerating and Air-
Conditioning Engineers (ASHRAE) 486
 - The American Conference of Governmental Industrial
Hygienists (ACGIH) 486
 - Heat Stress 487
 - Cold Stress 488
 - National Institute for Occupational Safety and Health (NIOSH)..... 488
- Standards in China 490
 - National Standard of the People’s Republic of China:
Evaluation Standard for Indoor Thermal Environments in
Civil Buildings, GB/T 50785-2012..... 490
- Standards in the United Kingdom..... 491
 - BS 7915 (1998): Ergonomics of the Thermal Environment:
Guide to Design and Evaluation of Working Practices for
Cold Indoor Environments 494
 - BS 7963 (2000): Ergonomics of the Thermal Environment:
Guide to the Assessment of Heat Strain in Workers Wearing
Personal Protective Equipment..... 494
 - Proposed British Standard: Specification of Physiological
Measuring Instruments..... 495
- European Standards (CEN)..... 495
- Example of the Application of International ISO Standards to
the Assessment of a Hot Environment 496
 - Example 496
 - ISO Assessment 497
- Example of the Application of International (ISO) Standards for
the Assessment of Moderate Environments 498
 - Example 498
 - Method..... 498
- Example of the Application of International (ISO)
Standards for the Assessment of Cold Environments 500

Example.....	500
Method.....	500
Chapter 19 Weather, Climate Change and Energy Use	503
Introduction	503
Meteorological Observations	504
Weather Stations	504
Global Databases	505
Universal Thermal Climate Index (UTCI)	505
Future Development and Application of the UTCI.....	509
Climate Change	511
Human Thermal Environments and Energy Use	512
Chapter 20 People in Extreme Heat and Cold, Hypobaric and Hyperbaric Environments, Water, Space and Extreme Sport	515
Introduction	515
People in Extreme Heat.....	515
Human Response to the ‘Hottest Place on Earth’	516
People in Extreme Cold.....	518
Human Response to the ‘Coldest Place on Earth’	518
People Under Pressure.....	519
People in Hypobaric Environments.....	520
Heat Exchange in Hypobaric Environments	523
People on Top of the World	524
People in Aeroplane Cabins	524
People in Hyperbaric Environments	525
Compressed Air Tunnels	525
People in Water	526
Cold Water Survival	528
Frozen Terrain, Snow, Rain, Wind and Floods.....	529
People in Space	530
Extreme Sport.....	531
Appendix 1	533
Appendix 2	539
Appendix 3	543
References	545

Preface to the Third Edition

Since the second edition of *Human Thermal Environments* was published in 2003, the world has embraced electronic communication, and this has provided true globalisation of the subject. It was always the case that there was international communication and collaboration between scientists, but this is now 'instant', natural and expected practice. There are many avenues for communication, from the traditional scientific paper, which in paper or electronic form still provides the respected source of peer-reviewed knowledge, to widely available conference proceedings, numerous and varied websites, social networks, blogs and many more. Scientists and practitioners benefit from the exchange of information and best practice across the world, and this provides a continued role for this book as a basic and comprehensive text and common reference. This third edition provides the most up-to-date and comprehensive coverage available of the principles and practice of human response to thermal environments.

All chapters have been revised and updated, and there are significant additions. There are new sections and chapters on the testing and development of clothing; adaptive models; thermal comfort for special populations; thermal comfort for special environments; extreme environments, the weather, outdoor environments and climate change. Chapters 1 through 7 present fundamental principles. Chapter 1 describes the six basic variables that make up human thermal environments and the fundamental principles of heat transfer between a person and his or her environment. Chapter 2 describes how to use those principles to create a heat balance equation for a person in a thermal environment and how to conduct a thermal audit that can be interpreted to predict and assess the responses of people to hot, moderate and cold environments. Chapters 3 and 4 describe physiological and psychological responses. New thinking and research is presented, as well as an extension of the presentation of behavioural thermoregulation, which is at the forefront of new methods and adaptive models which have created much interest and activity across the world. Chapter 5 is concerned with measuring methods and includes specification of instruments for measuring the environment, personal monitoring systems and specification of physiological instruments. The natural wet bulb temperature and its prediction is considered, as well as meteorological measurements and databases available on the Internet. Chapter 6 is concerned with dehydration and water requirements in response to human thermal environments. Control of body water, indicators of dehydration and practical recommendations for drinking are provided, with a fuller consideration of sporting activities than in the previous edition. Chapter 7 brings all of the fundamental principles together into thermal models which, as predicted in previous editions, have become an integral part of assessment and are being proposed as a basis for a universal approach to the subject. Thermal models have taken their place as an integrated part of the subject's activity, and their role in computer-aided environmental design has become established. A new initiative to provide an International Organization for Standardization (ISO) model is presented,

as well as developments in a model that have led to the new Universal Thermal Climate Index (UTCI).

Chapters 8 through 10 are concerned with metabolic heat and clothing. Chapter 8 considers how to measure and estimate metabolic heat production. Chapter 9 describes the thermal properties of clothing, and a new Chapter 10 considers the testing and development of clothing.

Chapters 11 through 15 cover thermal comfort, heat stress and cold stress, all of which have had significant developments. There are now three chapters on the important area of thermal comfort. Chapter 11 provides the fundamental principles and methods for assessment of thermal comfort. It includes adaptive models and new approaches and perspectives on thermal comfort. Responses to specific environments are described in Chapter 12. Responses of specific populations are described in Chapter 13. New developments in heat stress assessment are presented in Chapter 14, which includes developments in the method of assessment using the WBGT index as well as the predicted heat strain (PHS) index, which has been adopted in international standards. Chapter 15 describes responses to the cold and includes the new wind chill temperature as well as developments in working practices.

Chapter 16 considers human performance in thermal environments and is enhanced with a description of recent studies and approaches from a global perspective. Chapter 17 is updated and considers burns on contact with hot surfaces; sensation caused by contact with moderate surfaces; and discomfort, pain and loss in performance caused by contact with cold surfaces. This remains one of the few comprehensive treatments available in this area. Chapter 18 reflects a major contribution to the application of the subject with the publication, revision and development of international standards, now essential reading for the practitioner. Much has taken place since 2003, and this chapter provides the most up-to-date position. A new Chapter 19 considers the weather, outdoor environments and climate change. These are important issues for the future and will require an understanding of how people respond to thermal environments which are not typical of those they have been used to in the past. A new Chapter 20 covers extreme heat and cold and uses the principles presented earlier in the book to discuss how people respond up mountains, in compressed air, in deserts, on frozen terrain and in snow, rain, wind and floods. It also considers environments in space, in tunnels, in water, underwater and in crowds. Expeditions and a global perspective are also covered. This complements the new material on sports events, fun runs, cold snaps and heat waves presented in earlier chapters.

K.C. Parsons
Loughborough, 2013

Preface to the Second Edition

Since the first edition of *Human Thermal Environments* was published in 1993, the subject has moved into exciting times. While fundamental principles are accepted, knowledge has increased, methods of application are used and some are controversial. From a base in military research and studies of fit, young people, there is now a recognition of the importance of the subject in all aspects of life worldwide. Many of the ideas expressed in the first edition have come to fruition such as recognition of the six basic parameters (variables) as an essential starting point and the use of computers. The first edition recorded work up until the 1990s and may have stimulated research and application after that. It was particularly important in describing work in the 1980s when the foundations for new approaches were established. Developments that were at an early stage are now accepted. This second edition reports activity and progress into the twenty-first century while maintaining the description of the fundamentals of the subject and its development.

Programmes of European research have been a feature of the 1990s and beyond as the European Community has integrated activities over its member countries, stimulated co-operative research across countries and laboratories, industry, the military, consumers and other interested parties. Globalisation including worldwide electronic communication has had significant effects. New approaches to health and safety requirements have stimulated research and 'useable methods' and risk assessment strategies have become an issue. In heat stress the predicted heat strain assessment method has been developed, in cold stress working practices in industrial work are being established and the WCI reviewed, and in thermal comfort the PMV/PPD index hangs on as the agenda has moved to behavioural and adaptive approaches. Global databases of the results of collections of laboratory and field studies, made available on the worldwide web, can now allow quality control and research across the world to perform analysis on raw data. There has been an interest in special groups (e.g. people with disabilities) and special environments (e.g. vehicles, chilled ceiling and displacement ventilation). Knowledge of human skin contact with hot, moderate and cold surfaces has been developed, integrated and reported as part of the whole series of international standards that were first described at an early stage in the first edition and are now fully updated in this second edition. They provide an influential role in determining the direction of the subject and in stimulating research activity. New developments have provided new opportunities but we should not forget that the integrated subject of human thermal environments is based upon responses of people and the same fundamental principles apply. The second edition has introduced new developments since the previous edition while still maintaining a comprehensive description of the essentials of the subject.

All chapters have been revised, most with significant additions and there are new chapters on dehydration and water requirements and on thermal comfort for special populations, special environments and adaptive modelling. Chapters 1 to 7 present fundamental principles. Chapter 1 describes the six basic variables that make

up human thermal environments and now includes the effects of solar radiation. Improvements to the heat balance equation include the effects of clothing ventilation and practical application is enhanced with a description of the thermal audit which will become a fundamental starting point in all human thermal environments assessments. Chapters 2 and 3 describe physiological and psychological responses. The controversial selective brain cooling is discussed as well as developments in behavioural thermoregulation. Chapter 4 is a new chapter which marks the increasingly recognised importance of dehydration and water requirements in responses to human thermal environments. Control of body water, indicators of dehydration and practical recommendations for drinking are provided. Chapter 5 is concerned with measuring methods and now includes personal monitoring systems and specification of physiological instruments. Chapters 6 and 7 are concerned with metabolic heat and clothing. New techniques, including the doubly labelled water method and CO₂ build-up in rooms, are presented as well as developments in clothing ventilation and active clothing. Chapters 8, 9, 10 and 11 cover thermal comfort, heat stress and cold stress, all of which have had significant developments. The adaptive approaches to thermal comfort are described as well as response to specific populations and environments. New developments in heat stress assessment are presented, in particular the new predicted heat strain method that is being proposed as an International Standard. The description of the original research for the wind chill index is now described in detail as it comes under scrutiny and new proposals are developed. Chapter 12 is enhanced with the description of recent studies and approaches, in particular, the importance of the role of distraction in reducing productivity. Chapter 13 is significantly enhanced beyond consideration of hot surfaces with the entirely new sections on contact with moderate and cold surfaces, reflecting much improved knowledge and data in those areas. Chapter 14 reflects a major development in the application of the subject with the publication, revision and development of international standards, now essential reading for the practitioner. Chapter 15 has also been updated with significant developments. As predicted in the first edition, thermal models have taken their place as an integrated part of the subject's activity and their role in computer aided environmental design is becoming established.

K.C. Parsons
Loughborough, 2002

Preface to the First Edition

Responses to thermal environments play a major role in human existence. All humans have exhibited physiological and behavioural responses to heat and cold, from cave men, through ancient civilisations to the present day. Over the last few centuries such responses have undergone systematic scientific investigation. In parallel with major scientific discoveries, principles have been established and during the twentieth century these have been formalised into methods used in environmental design and evaluation. Technology has played a supporting role and in recent years the so-called information technology revolution has provided new opportunities for the development and application of well established principles and understanding. For example, in areas of environmental measurement, thermal models and in computer aided environmental design. Much is known and the foundations have been laid; however much is still to discover in this subject. What is certainly true is that there is greater than ever interest and activity in the area.

The book presents knowledge concerning human responses to hot, moderate, and cold thermal environments for people exposed to air at normal atmospheric pressure. A comprehensive and integrated approach to the subject is taken, defining human thermal environments in terms of six basic parameters: air temperature; radiant temperature; humidity and air velocity of the environment; the clothing worn and the activity of the person. Much of the book is concerned with how these parameters interact to produce physiological and psychological responses and how they, in turn, will affect human health, comfort, and performance.

The underlying principles, derived from the component disciplines of physics, physiology, and psychology, are described as are methods used in the practical assessment of thermal environments. An historical perspective is often taken to enhance description and understanding of current methods and techniques.

In Chapters 1 to 6 fundamental principles are presented. Chapter 1 defines the six basic parameters and demonstrates how they interact to influence heat exchange between the body and the environment. The analysis of heat transfer leads to the body heat balance equation, a fundamental concept in the rational method for assessing human thermal environments. Chapters 2 and 3 cover physiological and psychological responses. Human thermoregulation and body temperature are described, as are psychological and psycho-physical responses and perspectives. Chapter 4 is concerned with measurement of the basic environmental parameters, physiological responses and psychological responses. The thermal index is introduced as a fundamental assessment technique. Chapters 5 and 6 are concerned with the principles and estimation of the basic parameters, metabolic heat production, and clothing insulation.

Chapters 7, 8 and 9 consider thermal comfort, heat stress, and cold stress. There has been much activity in this area and recent developments, particularly new rational thermal indices, are described. Interference with activity, performance, and productivity is considered in Chapter 10. A systematic approach is taken and fundamental

research reviewed. A performance model is discussed, as well as ways forward, in this area of great economic concern.

Chapters 11, 12 and 13 present topics not previously presented in detail that will be of great interest and influence in the future. Skin reaction on contact with solid surfaces is difficult to study where burns occur, for ethical reasons. Knowledge of temperatures that produce burns is needed however to aid in the design of products. Scientific findings and practical suggestions are presented as a contribution to this highly controversial area. The development of international standards has been a feature of the last ten years and, with segmented world markets, will continue to be of interest. Chapter 12 describes current developments.

Digital computers and developments in knowledge and techniques have led to the availability of thermal models. Fundamental principles and important and influential models are described. The possibility of computer aided design in this area is demonstrated.

There is no doubt that the practice of this subject is best performed using computers. For example, in recent years my students of climatic ergonomics, physiology, and psychology routinely use software in all aspects of their project and survey work. Sufficient detail is provided in the book to allow the production of software. Source listings of some important computer programs are provided in the appendices. In the first plan of the book a suite of programs was to be included. However, after consideration, I decided to refer to texts where software could be obtained in disk form. This will allow the reader access to easy updates and save errors and laborious typing of source code. All of the equations and models referred to in this book are available on disk for microcomputers from references provided in the text.

K.C. Parsons
Loughborough, 1992v

Acknowledgements to the Third Edition

In addition to people acknowledged in the first and second editions of this book, I acknowledge and thank those who supported me for this third edition. Since the previous edition I have been head of the Department of Human Sciences, dean of science and pro-vice chancellor for research at Loughborough University. I thank Pam Taylor for her outstanding support over that period. George Havenith and Simon Hodder have integrated the Human Thermal Environments laboratory into the Environmental Ergonomics Research Centre, and I am grateful for their support. Students are the lifeblood of a university, and research students motivate and support academics. I am grateful to all of my students and in particular to my PhD students: Julia Scriven, Roger Haslam, Paul Wadsworth, Wen Qi Shen, Mike Neale, Marc McNeill, Lisa Bouskill, Mandy Stirling, Simon Hodder, Damian Bethea, Ju Youn Kwon and Lisa Kelly, and to my MPhil students: Paul Underwood and Paddy Stennings, for being there, supporting me and producing excellent research. I am proud that they have gone on to greater things and of any contribution I may have made to help them on their way. Mandy Stirling obtained her PhD in water requirements and went on to do significant work for the fire service before her death at a young age with unfulfilled potential. She was a respected scientist with a vibrant personality, and we all miss her. Professor Bernard Metz provided support in my work with international standards. He was a pioneer and inspiration as well as a wise, warm and generous colleague. The world of ergonomics gained much from him and lost greatly on his passing. I gained much inspiration from Professor Ole Fanger, who not only gave us his landmark book *Thermal Comfort* but taught us how to appreciate the great things in life. His passing was the end of an era, and his legacy includes the next generation he inspired. I would also acknowledge the work of Fergus Nicol and Mike Humphreys, as well as Bizhan Li, Runming Yao, Richard De Dear, Shin Itchi Tanabe, Ed Arens, Gail Brager and the group at Berkeley, United States. They provided us with new perspectives on thermal comfort and ongoing stimulating debate, much of which was discussed and developed at the series of conferences inspired by Fergus and Mike and held at Cumberland Lodge, Windsor Great Park, United Kingdom.

I acknowledge the work of Ingvar Holmér, who recently retired from Lund University in Sweden. Ingvar moved the subject on with his energy, international perspective and insight, particularly in the area of cold stress and clothing. He inspired and created opportunities for those around him, and I am grateful to have worked with him over many years. I acknowledge the support of colleagues on British Standards Institution (BSI), European Standards (EN) and International Organization for Standardization (ISO) committees. These include B. Olesen, K. Kurakata, H. Sato, G. Havenith, I. Holmér, B. Kampmann, H. Rintamäki, S. Sawada,

Y. Tochihara, F. D'Ambrosio-Alfano, J.-Y. Kwon, J.-Y. Lee, S. Yokoyama, T. Bernard, O. Jay, S. Hodder, S. Harker, D. Gardner-Bonneau, R. Graveling and H. Howarth. Yutaka Tochihara has been a great supporter who retired recently after many years of inspiring students and researchers, both internationally and in his laboratory at Kyushu University in Japan.

It seems a long way from Old Hartley County Primary School in Seaton Sluice, and I acknowledge the support of my late father Eric, my mother Florence, my sister Christine and brother Ean. Finally, I thank my family. Benjamin, Anna and granddaughter Nancy are thriving in Brighton, Hannah and Richard in London and Samuel in Exeter. Most of all I thank my wife, Jane.

Acknowledgements to the Second Edition

In addition to those acknowledged in the first edition, I would like to thank all those who have supported me with the second edition. The death of Pharo Gagge of the J. B. Pierce Foundation, Yale, USA was a great loss to the subject from which it has yet to recover and his work makes a significant contribution to this book. Ralph Goldman, now retired, has continued to inspire as have Ole Fanger and Bjarne Olesen from Denmark and Professor Bernhardt Metz from France; Rainer Goldsmith, now retired from the Department of Human Sciences at Loughborough University, influenced us all with his extensive knowledge and experience, as did the late Ernest Hamley who kept me in touch with the history of the subject and always had a story to tell. I am particularly appreciative of the support of Ingvar Holmér from Sweden who has consistently pursued an international agenda for the subject and has stimulated many symposia, research projects and conferences worldwide. I am also grateful to Victor Candas for his perceptive advice and experience concerning human thermal physiology and thermoregulation and to Byron Jones and Elizabeth McCullough from KSU, USA for the high quality of their work and the unstinting way in which they disseminate it to the wider scientific community.

I acknowledge the support of Cathy Bassey, John Fisher, David Fishman and Sina Talal of the BSI and Murielle Gauvin from AFNOR for their work with ISO/TC 159 SC5 and CEN/TC 122 WG11. I also acknowledge Geoff Crockford, Margaret Hanson, Alan Snary, W. R. Withey and Tony Youle from BSI committees. ISO/TC 159 SC5 WG1 has continued to provide a forum for international debate. We have grown old together and I acknowledge the contributions of G. Alfano, V. Candas, G. Crockford, D. Gabay, H-J. Gebhardt, B. Griefahn, J. Hassi, G. Havenith, I. Holmér, R. Ilmarinen, B. Kampmann, G. Langkilde, J. Malchaire, B. Olesen, H. Rintamäki, S. Sawada and Y. Tochihara.

In recent years I have been grateful for the discussions of developments in thermal comfort with Mike Humphreys and Fergus Nicol of Oxford Brookes University and Dennis Loveday, Ahmed Taki and Genhong Zhou from Loughborough.

The Department of Human Sciences at Loughborough has provided a unique blend of Ergonomics, Psychology and Human Biology, creating a stimulating environment from which to view different perspectives of the subject. The pioneering work of Professor Will Floyd, Brian Shackel and Stuart Kirk as well as that of Peter Jones, Peter Stone, Mike Cooke and others has grown into significant and productive academic body and I am proud to have carried the banner forward as Head of the Department since 1996. I acknowledge the following academic colleagues: Dr. T. Baguley, Dr. K. Brooke-Wavell, Dr. S. Brown, Dr. J. Brunstrom, Professor N. Cameron, Dr. J. Cromby, Dr. C. Crook, Professor K. Eason, Dr. H. Gross, S. Harker, Dr. R. Haslam, Dr. G. Havenith, Dr. R. Hooper, Professor J. Horne, Dr. P. Howarth,

Professor M. Lansdale, Dr. N. Mansfield, Dr. S. Mastana, Dr. D. Middleton, Professor K. Morgan, Dr. L. Reyner, Dr. E. Rousham and M. Sinclair.

I would also acknowledge the support of members of the Human Thermal Environments Laboratory including George Havenith, Ollie Jay, Shuna Powell, Karen Bedwell, Trevor Cole, Lynda Webb and my PhD students: Julia Scriven, Roger Haslam, Paul Wadsworth, Wen Qi Shen, Mike Neale, Marc McNeill, Lisa Bouskill, Mandy Stirling, Damian Bethea and Simon Hodder.

Hilarie Kemp helped me recover the previous manuscript and kept me on track with the new one. I am grateful to her for extensive support with book production, the enthusiasm and dedication showed, for her careful attention to detail and for finding amusement in parts of the text (some of which was intended).

Finally I would acknowledge the support of my family. Benjamin has graduated in English and is training to be a journalist. Hannah is reading Italian and Samuel is embarking on his secondary school career, with a passion for rugby. Jane, as ever, is there for all of us.

Acknowledgements to the First Edition

I am responsible for any errors and some of the inspiration and knowledge presented in this book. I have benefited greatly from the advice, friendship, and openness of many experts throughout the world. These particularly include colleagues from the Department of Human Sciences at Loughborough, those on British, European, and International Standards committees, and fellow members of the Ergonomics Society and of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

I first met Fred Roules on an aeroplane between Copenhagen and London. He invited me to give a presentation at an ASHRAE symposium he was organising in New York. After the symposium I visited Pharo Gagge at the J.B. Pierce Laboratory, Yale and stayed with Pharo and his wife Edwina in their home. It was a most hospitable, inspirational, and informative visit for which I will always be grateful. I would like to thank Pharo Gagge of the J.B. Pierce Laboratory and also Fred Rohles, Elizabeth McCullough and Byron Jones of the Institute for Environmental Research, Kansas, for their help, advice, and support.

I first attended the ISO Working Group concerned with the Ergonomics of the thermal environment in 1983. The group had been meeting since mid 1970s and the United Kingdom had joined late. Despite some scepticism, but skilfully managed by the Chairman, Gerard Aubertin, standards were, and still are being, produced. The international experts in the group debated many aspects of the subject and, over the years, undoubtedly made a major contribution in particular in stimulating interest and research. I was privileged to be part of this and acknowledge the contribution of members who included Gerard Aubertin, Gaetano Alfano, Ole Fanger, François Grivel, George Havenith, Thomas Hettinger, Ingvar Holmér, Jacques Malchaire, Bjarne Olesen, Jean-Jacques Vogt, and Joseph Yoshida. I would also acknowledge Bernard Metz and Harald Siekmann, colleagues from European Standards committees, and Peter Crabbe, Geoff Crockford, David Fishman, Rod Graves and Ron McCaig from the BSI committee concerned with human response to the thermal environment.

There have been a number of books on aspects of human response to thermal environments and I have in particular often referred to two over the last ten years. These are *Indoor Climate* by D. A. McIntyre and *The stress of hot environments* by D. McK Kerslake. I would acknowledge the contribution of the authors. I would also acknowledge the advice of Ralph Goldman previously from USARIEM in the USA and of Mike Haisman when previously at the APRE in the UK. Mike Haisman provided continued enthusiasm, support, and advice throughout the thermal modelling work carried out with Roger Haslam and the work on the MAPS system with Paul Wadsworth, which integrated thermal models into a computer enquiry handling system.

Colleagues within the Department of Human Sciences have provided support that I acknowledge. These include Rainer Goldsmith, Ernest Hamley, Jim Horne, Stuart Kirk, Brian Shackel, and Peter Stone. I would also like to thank Mary Hewitt for helping type the manuscript, the many students who have produced projects and theses on all aspects of the subject and maintained my interest and the research workers, past and present, in the Human Modelling Group at Loughborough.

The greatest acknowledgement is to my family for their support: Jane, Benjamin, Hannah and Samuel.

Author



Ken Parsons is professor of environmental ergonomics at Loughborough University. He was born on January 20, 1953, in northeastern England in a coastal village called Seaton Sluice. He graduated from Loughborough University in ergonomics in 1974, obtained a postgraduate certificate in education in mathematics with a distinction from Hughes Hall, Cambridge University in 1975 and was awarded a PhD in human response to vibration in 1980, from the Institute of Sound and Vibration Research, Southampton University. He founded the Human Thermal Environments Laboratory at Loughborough in 1981 and was awarded a certificate in management from the Open University in 1993. Ken became head of the Department of Human Sciences in 1996, Dean of Science in 2003 and pro-

vice chancellor for research from 2009 to 2012. He was chair of the United Kingdom Deans of Science from 2008 to 2010.

In 1992, he received the Ralph G. Nevins award from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) for 'significant accomplishments in the study of bioenvironmental engineering and its impact on human comfort and health'. The Human Thermal Environments laboratory was awarded the President's Medal of the Ergonomics Society in 2001. He is one of the co-authors of the British Occupational Hygiene Society publication on thermal environments and has contributed to the Chartered Institute of Building Services Engineers publications on thermal comfort as well as to the *ASHRAE Handbook: Fundamentals*.

He is a fellow of the Institute of Ergonomics and Human Factors, the International Ergonomics Association and the Royal Society of Medicine. He is a registered European Ergonomist and has been an elected member to the council of the Ergonomics Society. He has been a scientific advisor to the Defence Evaluation Research Agency and the Defence Clothing and Textile Agency and a member of the Defence Scientific Advisory Committee. He has been both secretary and chair of the thermal factors committee of the International Commission on Occupational Health (ICOH), chair of the CNRS advisory committee to the Laboratoire de Physiologie et Psychologie Environnementales in Strasbourg, France, and is a life member of the Indian Ergonomics Society. He was a visiting professor to Chalmers University in Sweden and is a member of the committee of the International Conference on

Environmental Ergonomics. He is an advisor to the World Health Organization on heatwaves and a visiting professor to Chongqing University in China, where he has been appointed as a leading academic to the National Centre for International Research of Low Carbon and Green Buildings. He is co-editor in chief of the journal *Applied Ergonomics* and is on the editorial boards of the journals *Industrial Health*, *Annals of Occupational Hygiene* and *Physiological Anthropology*.

He is co-founder of the United Kingdom Indoor Environments Group and a founding member of the UK Clothing Science Group, the European Society for Protective Clothing, the Network for Comfort and Energy Use in Buildings and the thermal factors scientific committee of the ICOH. He is chair of ISO TC 159 SC5 'Ergonomics of the Physical Environment' and convenor to the ISO working group on integrated environments, chair of the British Standards Institution committee on the ergonomics of the physical environment and convenor of CEN TC 122 WG11, which is the European standards committee concerned with the ergonomics of the physical environment.

List of Notations

The choice of notation is based on that used by the American Society of Heating, Refrigerating and Air-Conditioning Engineers in Chapter 8 of *Handbook—Fundamentals* (1989). Standard definitions of terms, symbols and units can also be found in ISO 13731 (2001).

a, b	Constants used in the calculation of air velocity from kata cooling time	ND
A	Activity factor for calculation of pumping effects on clothing insulation	ND
A_{cl}	Surface area of clothed body	m^2
A_{conv}	Percentage of body surface area covered by a garment	%
A_D	Du Bois body surface area	m^2
A_p	Projected area of the body	m^2
A_r	Effective radiating area of the body	m^2
b_i	Thermal penetration coefficient for material i	$J s^{-1/2} m^{-2} K^{-1}$
B	Behaviour	ND
B	Exponent used in psychophysical power law	ND
BM	Basal metabolic rate	$W m^{-2}$
c	Specific heat capacity	$kJ kg^{-1} ^\circ C^{-1}$
C	Convective heat loss per unit area	$W m^{-2}$
C_A	Weight of subject clothed after exposure	kg
C_B	Weight of subject clothed before exposure	kg
$C_{p,bl}$	Specific heat capacity of blood	$kJ kg^{-1} ^\circ C^{-1}$
C_{res}	Dry respiration heat loss per unit body surface area	$W m^{-2}$
$C_{SIG_{sk}}$	Effector-controlling signal for vasoconstriction	ND
d	Diameter of spherical centre	m
dt_{sk}	Clothing insulation index derived from mean skin temperature of subjects when clothed and unclothed	$^\circ C$
D	Distance of load carriage	m
D_c	Magnitude estimate of cold discomfort	ND
DRY	Dry heat loss from the skin	$W m^{-2}$
D_w	Magnitude estimate of warm discomfort	ND
E	Environment	ND
E	Evaporative loss per unit body surface area	$W m^{-2}$
E_{dif}	Evaporative loss by diffusion through skin per unit area	$W m^{-2}$
EE	Energy equivalent of burning food in oxygen	$Wh (LO_2)^{-1}$
E_{max}	Maximum evaporative potential per unit area	$W m^{-2}$
E_p	Predicted evaporation rate	$W m^{-2}$

E_{req}	Required evaporative loss per unit area for heat balance	W m^{-2}
E_{res}	Evaporative loss from respiration	W m^{-2}
E_{rsw}	Evaporation of sweat secreted due to thermoregulatory control	W m^{-2}
ESAT	Burton and Edholm equivalent still air temperature	$^{\circ}\text{C}$
E_{sk}	Total evaporative heat loss from the skin	W m^{-2}
EST	Burton and Edholm equivalent shade temperature	$^{\circ}\text{C}$
E_{sw}	Total evaporation rate due to sweating	W m^{-2}
ET	Effective temperature	$^{\circ}\text{C}$
f	Standard temperature and pressure, dry (STPD) reduction factor	ND
f	Partial pressure of water vapour in air	mmHg
f_{d}	Clothing area factor	ND
f_{p}	Projected area factor	ND
F	Kata factor	m cal cm^{-2}
FCO_2	Fraction of carbon dioxide in expired air	ND
F_{eff}	Effective radiation area factor	ND
FO_2	Fraction of oxygen in expired air	ND
F_{pcl}	Permeation efficiency factor	ND
$F_{\text{p-n}}$	Angle factor between a person, p and a surface, n	ND
g	Radiant response ratio	ND
G	Mass velocity	$\text{kg m}^{-2} \text{s}^{-1}$
h	Combined heat transfer coefficient	$\text{W m}^{-2} \text{K}^{-1}$
h_{c}	Convective heat transfer coefficient	$\text{W m}^{-2} \text{K}^{-1}$
h_{d}	Thermal conductance of a clothing ensemble	$\text{W m}^{-2} \text{K}^{-1}$
h_{e}	Evaporative heat transfer coefficient	$\text{W m}^{-2} \text{kPa}^{-1}$
h_{fg}	Heat of vaporisation of water	kJ kg^{-1}
h_{r}	Radiative heat transfer coefficient	$\text{W m}^{-2} \text{K}^{-1}$
H	Height	m
H	Metabolic heat production per unit body surface area	W m^{-2}
HR	Heart rate	beats per min
HR_{e}	Residual component of heart rate	beats per min
H_{res}	Total respiratory heat loss	W m^{-2}
HR_{m}	Component of heart rate due to work	beats per min
HR_{N}	Component of heart rate due to emotional response	beats per min
HR_0	Heart rate while at rest	beats per min
HR_{s}	Component of heart rate due to static exertion	beats per min
H_{sk}	Total heat loss at the skin	W m^{-2}
HR_{T}	Component of heart rate due to thermal strain	beats per min
HR_{r}	Heart rate after recovery	beats per min

i_{cl}	Clothing vapour permeation efficiency	ND
i_m	Moisture permeability index (clothing)	ND
I_a	Thermal insulation of the boundary layer on a nude person	clo, $m^2\text{ }^\circ\text{C W}^{-1}$
I_{cl}	Intrinsic clothing insulation	clo, $m^2\text{ }^\circ\text{C W}^{-1}$
I_{cle}	Effective clothing insulation	clo, $m^2\text{ }^\circ\text{C W}^{-1}$
I_{clo}	Effective clothing insulation in clo units	clo
I_{clu}	Effective clothing insulation of a garment	clo, $m^2\text{ }^\circ\text{C W}^{-1}$
$I_{clu,i}$	Effective clothing insulation of garment i	clo, $m^2\text{ }^\circ\text{C W}^{-1}$
I_{ecl}	Resistance of clothing to the transfer of water vapour	$m^2\text{ kPa W}^{-1}$
I_{ea}	Resistance of air layer to the transfer of water vapour	$m^2\text{ kPa W}^{-1}$
I_{EQUIV}	Equivalent clothing insulation	clo, $m^2\text{ }^\circ\text{C W}^{-1}$
IREQ	Clothing insulation required	clo, $m^2\text{ }^\circ\text{C W}^{-1}$
IREQ _{min}	Clothing insulation required for thermal equilibrium	clo, $m^2\text{ }^\circ\text{C W}^{-1}$
IREQ _{neutral}	Clothing insulation required for thermal comfort	clo, $m^2\text{ }^\circ\text{C W}^{-1}$
I_{res}	Resultant clothing insulation	clo, $m^2\text{ }^\circ\text{C W}^{-1}$
I_t	Total clothing insulation	clo, $m^2\text{ }^\circ\text{C W}^{-1}$
k	Constant of psychophysical power law	ND
k_s	Thermal conductivity for sensible heat	$\text{W m}^{-2}\text{ }^\circ\text{C}$
K	Heat transfer by conduction	W m^{-2}
K_e	Thermal conductivity of water vapour	$\text{W m}^{-2}\text{ kPa}^{-1}$
L	Thermal load per unit body area	W m^{-2}
LR	Lewis relationship	K kPa^{-1}
M	Metabolic free energy production per unit body area	W m^{-2}
M_{act}	Component metabolic energy due to subject's activity	W m^{-2}
M_{bl}	Blood flow	$\text{kg s}^{-1}\text{ m}^{-2}$
Met	Metabolic rate symbol used by Nishi and Gagge (1977)	W m^{-2}
M_i	Metabolic rate representative of activity i	W m^{-2}
M_m	Component of metabolic rate due to whole-body movement	W m^{-2}
M_{net}	Metabolic heat load in Givoni/Goldman model	W
M_p	Component of metabolic rate due to posture	W m^{-2}
M_{rsw}	Rate at which sweat is secreted	$\text{kg s}^{-1}\text{ m}^{-2}$

M_{shiv}	Component of metabolic heat due to shivering	W m^{-2}
M_{w}	Component of metabolic rate due to type of work	W m^{-2}
NA	Weight of nude subject after exposure	kg
NB	Weight of nude subject before exposure	kg
O_{e}	Fractional oxygen content of expired air	ND
O_{i}	Fractional oxygen content of inspired air	ND
P	Person	ND
P	Measured atmospheric pressure	kPa
P_1	Pulse rate from 30 s to 1 min during recovery	beats per min
P_2	Pulse rate from 1.5 to 2 min during recovery	beats per min
P_3	Pulse rate from 2.5 to 3 min during recovery	beats per min
P_{a}	Partial pressure of water vapour in air	kPa
$P_{\text{sk,s}}$	Saturated water vapour pressure at skin temperature	kPa
P_{swb}	Saturated water vapour pressure at aspirated wet bulb temperature	kPa
Q_{crsk}	Combined thermal exchange between body core and skin	W m^{-2}
Q_{lim}	Heat storage limit	W h m^{-2}
Q_{res}	Total rate of heat loss through respiration	W m^{-2}
Q_{sk}	Total rate of heat loss from the skin	W m^{-2}
r	Efficiency of sweating	ND
R	Radiative heat loss per unit area	W m^{-2}
R_{c}	Thermal resistance of clothing, symbol used by Umbach (1988)	$\text{m}^2 \text{ } ^\circ\text{C W}^{-1}$
R_{cl}	Intrinsic thermal insulation of clothing	$\text{m}^2 \text{ K W}^{-1}$
R_{ct}	Total thermal resistance of clothing, used by Umbach (1988)	$\text{m}^2 \text{ } ^\circ\text{C W}^{-1}$
R_{e}	Water vapour resistance of clothing, used by Umbach (1988)	$\text{m}^2 \text{ kPa W}^{-1}$
$R_{\text{e,cl}}$	Intrinsic evaporative resistance of clothing	$\text{m}^2 \text{ kPa W}^{-1}$
R_{et}	Total water vapour resistance of clothing, used by Umbach (1988)	$\text{m}^2 \text{ kPa W}^{-1}$
$R_{\text{e,t}}$	Total evaporative resistance	$\text{m}^2 \text{ kPa W}^{-1}$
RM	Increase in heart rate per unit of metabolic rate	beats per min $\text{m}^2 \text{ W}^{-1}$
RQ	Respiratory quotient	ND
R_{s}	Solar load in index of thermal stress	W m^{-2}
RT	Recovery time	min
S	Rate of heat storage per unit area	W m^{-2}
S	Warmth sensation rating	ND
SW	Sweating required, used by Givoni (1963)	W m^{-2}
SW_{max}	Maximum sweat rate that can be achieved by persons	W m^{-2}
SW_{p}	Predicted sweat rate	W m^{-2}
SW_{req}	Sweating required: required sweat rate index	W m^{-2}

t	Recorded temperature of expired air	°C
t_a	Air temperature	°C
t_b	Mean body temperature	°C
$t_{b,n}$	Mean body temperature for a person in thermal neutrality	°C
t_c	Contact temperature	°C
t_{cc}	Contact temperature if the solid surface were made entirely of the coating on the skin and corrected for type of contact	°C
t_{ch}	Chilling temperature index	°C
t_{cl}	Surface temperature of clothed body	°C, K
t_{con}	Contact temperature	°C
t_{cr}	Core temperature	°C
t_{db}	Dry bulb temperature	°C
t_{dp}	Dew point	°C
t_g	Globe temperature	°C, K
t_h	Temperature of hot body	°C
t_i	Temperature of surface i	°C
t_i	Time on activity i	min
t_k	Mean temperature of kata thermometer range	°C
t_{nwb}	Natural wet bulb temperature	°C
t_o	Operative temperature	°C
t_{pr}	Plane radiant temperature	°C
t_r	Mean radiant temperature	°C
t_{re}	Rectal temperature	°C
t_{ref}	Predicted equilibrium rectal temperature in Givoni/Goldman model	°C
t_{res}	Dry resultant temperature index	°C
t_s	Surface temperature	°C, K
t_{sh}	Body shell temperature	°C
t_{sk}	Mean skin temperature	°C
$t_{sk,n}$	Mean skin temperature for a person in thermal neutrality	°C
t_{ty}	Tympanic membrane temperature	°C
t_w	Mean temperature of surrounding walls	°C
t_{wb}	Aspirated wet bulb temperature	°C
T	Total time over all activities	min
T_{ceq}	Equivalent contact temperature index	°C
T_{core}	Mean core temperature of thermal model	°C
T_{eq}	Equivalent temperature	°C
T_{eq}	Equivalent temperature index	°C
T_{muscle}	Mean muscle temperature of thermal model	°C
$T_{pr,i}$	Plane radiant temperature in direction i	°C

T_{skin}	Mean skin temperature of thermal model	°C
T_u	Local air turbulence	ND
v	Air velocity (speed)	m s^{-1}
V	Ventilation rate	L s^{-1}
V_{ex}	Volume of expired air	L
VO_2	Oxygen uptake	mL kg min^{-1}
w	Skin wettedness	ND
w_{max}	Maximum skin wettedness that can be achieved by persons	ND
w_p	Predicted skin wettedness	ND
w_{req}	Required skin wettedness	ND
W	External mechanical work per unit area	W m^{-2}
W	Weight of load carried	kg
W_c	Comfort rating, used by Umbach (1988)	ND
W_{ct}	Comfort rating, used by Umbach (1988)	ND
W_{ex}	Mechanical work symbol from Givoni and Goldman (1973)	W
WK	Symbol for mechanical work, used by Gagge (1988)	W m^{-2}
W_{SIG_b}	Mean body temperature component of sweating controller signal	ND
$W_{\text{SIG}_{\text{er}}}$	Effector-controlling signal for vasodilation	ND
x	Average cloudiness in tenths	ND
Y	Mechanical efficiency of the body doing work	ND
Y	Subjective warmth vote	ND
Greek		
α	Absorptivity	ND
α	Azimuth angle	degree
α	Relative mass of skin to core	ND
β	Elevation	degree
ε	Emissivity	ND
η	Mechanical efficiency of work	ND
λ	Latent heat of evaporation	J kg^{-1}
λ	Wavelength	μm
μ	Viscosity of the air	kg m s^{-1}
Φ	Magnitude of stimulus	ND
Φ_0	Magnitude of stimulus at absolute perception threshold	ND
σ	Stefan–Boltzmann constant = 5.67×10^{-8}	$\text{W m}^{-2} \text{K}^{-4}$
ϕ	Relative humidity	ND
Ψ	Magnitude of sensation	ND

1 Human Thermal Environments

INTRODUCTION

The human body is subject to the laws of thermodynamics. The first law states that energy is neither created nor destroyed but can be transformed from one form to another. The second is that there is a natural direction of transfer. For heat, that is from a hot body to a cold one. In the case of the laws of physics, there is nothing special about people.

A living person generates heat from energy in food. To maintain an internal temperature of around 37°C, which is the human disposition, environmental conditions will determine whether that is too much heat, too little heat or just right. If the resting body does not lose heat to the environment, where it is totally insulated for example, the body temperature will rise at about 1°C per hour and the person will die in a few hours. In a heatwave or when wearing protective clothing, there will be reduced capacity to lose heat and it is important to ensure that sufficient heat is lost to the environment or transferred out of the body in some other way. In cold conditions, heat may have to be preserved in the body by the use of clothing or other mechanisms.

A living person is much more than a body mass undergoing heat generation and heat transfer. People exist in a social context; they have aspirations, emotions, opinions and behaviours. They experience pleasure and pain, satisfaction, comfort and discomfort, and environments can affect their health and performance. They are also active, and have worries, expectations, memories and models of the world. They test scenarios and predict the future, have religions, beliefs and cultures, as well as social networks, and they engage in discourse in their interaction with others and a global society. A comprehensive study of human thermal environments, especially when considering social and psychological phenomena such as thermal comfort and satisfaction, must consider people as a whole.

The sun, at a temperature of around 5500°C, provides heat to the earth at the top of the atmosphere at a rate of 1370 W m⁻² (the solar constant: the exact value depending on the orbit of the earth around the sun). Human existence, along with that of other organisms, depends on that energy. On the earth, the energy is transferred from place to place and from one form to another, hence creating a wide range of environments. This is aided by the spin of the earth and its tilt with respect to the sun, which causes spatial and temporal variations in energy due to day and night and the seasons. The atmosphere is a gas which is attracted to but not attached to the earth. It is that which maintains human life. The dynamic nature of the atmosphere (temperature variation, humidity, clouds, wind, rain, snow, etc.) is sensitive to

energy content. If energy is increased, as in the hypothesis of global warming, then there will be a consequent climate change as more intensive activity than before will cause extremes of climate and atypical weather. That is, cold where people are used to heat; hot where people are used to cold; high winds, extreme storms and floods or droughts where they have not occurred before, and more severe where they have; or even less extreme conditions in some areas than those expected.

The challenge for every person is to successfully interact with his or her local environment. The human body responds to environmental variables in a dynamic interaction that can lead to death if the response is inappropriate or if energy levels are beyond survivable limits, and it determines the strain on the body as it uses its resources to maintain an optimum state. In the case of the thermal environment, this will determine whether a person is too hot, too cold or in thermal comfort.

Air temperature, radiant temperature, humidity and air movement are the four basic environmental variables that affect human response to thermal environments. Combined with the metabolic heat generated by human activity and the clothing worn by a person, they provide the six fundamental factors (sometimes called the six basic parameters) that define human thermal environments. The general, but fundamental, point is that it is the interaction of the six factors to which humans respond. This was shown by Fanger (1970) in his classic book *Thermal Comfort*. It also applies for humans in hot or cold environments. Collins (1983) provides an example of an adult who skied down a slope with a child on his back. At the bottom of the slope the adult was hot and sweating. The child, however, suffered hypothermia. Metabolic heat production in the skiing adult had been more than enough to compensate for heat loss driven primarily by high relative air velocity across the body and low air temperatures. The child, however, had been inactive. The adult and the child had experienced very different human thermal environments and hence had very different responses.

The ability to lose heat by the evaporation of sweat is crucial to a person under heat stress. Environmental humidity is therefore of great importance, as is the nature of protective clothing. Death and heat illness in military personnel have been attributed to high metabolic heat production, radiant and air temperatures, and relatively impermeable protective clothing. Often, however, it is because there is a lack of understanding of the effects of the interaction of the six basic variables, and hence a lack of effective management systems to deal with them.

Often, environments are assessed or environmental limits are defined only in terms of air temperature. This is insufficient, as the other five factors are relevant. For example, thermal comfort in offices or vehicles may be greatly affected by solar radiation, and specifying comfort limits in terms of air temperature alone will be inadequate. That is not to say that reasonable assumptions cannot be made. In terms of thermal comfort, it is sometimes reasonable to specify comfort limits in terms of air temperature on the assumptions that radiant temperature equals air temperature, there is still air at 50% relative humidity, and that people in the environment wear 'normal' clothing and conduct light activity. However, it is better that assumptions are explicitly stated rather than imply that air temperature alone determines thermal comfort.

In specific situations, other factors will be influential; for example, a person's posture will greatly affect the heat exchange between the body and the environment. Behavioural factors can be important. Motivation, and the degree of acclimatisation

to heat, can play a major role in determining heat stress casualties in military exercises or in sports events. The six fundamental factors therefore provide a minimum requirement for a useful conceptual basis for the consideration of human thermal environments. How these contribute to heat transfer and human response is described in the following sections.

HEAT TRANSFER

Heat transfers from hot bodies to cold bodies and is driven by temperature difference. This is called sensible heat transfer and it can take place by conduction, convection and radiation. Heat can also be lost or gained without a temperature difference, by a change of state from liquid to gas (evaporation) and gas to liquid (condensation). This is called latent heat. Heat transfers between the human body and the environment by all of these mechanisms, and latent heat loss is particularly important when environmental temperatures are close to or greater than body temperatures.

CONDUCTION

Heat transfer through solids or stationary fluids is by conduction. It is driven by temperature difference, and the rate of flow depends on the thermal resistance of the material. As air has a relatively high thermal resistance, heat transfer by conduction from the body to the environment is relatively small when compared with other mechanisms and so it is often ignored. Conduction is relevant to human heat transfer, however, as it is one of the mechanisms for transferring heat from inside the body to the skin surface, as well as the heat transfer through clothing.

A general equation for heat flow by conduction (Q) is

$$Q = \frac{KA(T_2 - T_1)}{d} \quad (1.1)$$

where:

Q = rate of energy flow (W)

K = thermal conductivity ($\text{W m}^{-1} \text{K}$)

A = surface area of contact (m^2)

T_1 = temperature of the surface at lower temperature ($^{\circ}\text{C}$)

T_2 = temperature of the surface at higher temperature ($^{\circ}\text{C}$)

d = distance through which heat is transferred (m)

Equation 1.1 applies when the 'system' is settled and temperatures do not vary with time. This is called steady state. For non-steady-state conditions, where temperatures vary with time (t), the rate of heat storage (dQ/dt) and the temperature at any distance and time are given by Kerslake (1972) as

$$\frac{dQ}{dt} = K \frac{d^2T}{dx^2} \quad (1.2)$$

and

$$\frac{dT}{dt} = \frac{K}{\rho c} \frac{d^2T}{dx^2} \quad (1.3)$$

This demonstrates that the temperature (T) and the rate of change of the temperature will depend on the heat storage and the heat capacity per unit volume: density (ρ) \times heat capacity per unit mass (c). In effect, the rate of change of the temperature with time (dT/dt) is proportional to the rate of change of the temperature gradient (dT/dx) with distance (x), moderated by the thermal properties of the material. For the case where conditions are moving towards steady state, energy is required for heat storage to reach that condition and this is reflected in Equations 1.2 and 1.3.

CONVECTION

Convection is heat transfer by movement of a fluid. It involves conduction of heat from a solid surface to a moving fluid, absorption of the heat by the fluid, which raises its temperature, and the movement of the fluid at a higher temperature to areas of lower temperature by mixing and bulk movement. Associated with heat transfer by convection is the so-called boundary layer. This is where fluid of a higher temperature (heated by the body) than the environmental air temperature will be adjacent to the surface of the solid, and in effect provides additional insulation. The thickness and dynamics of this 'air' layer will be determined by temperature differences and the environmental conditions, particularly air velocity. Because heat transfer by convection involves fluid flow it can be studied to a great level of complexity using fluid dynamics. The simple equation for heat transfer by convection is

$$C = h_c (T_2 - T_1) \quad (1.4)$$

where ($T_2 - T_1$) is the temperature difference between the surface and the fluid and h_c is the convective heat transfer coefficient.

For a given structure, such as the human body, h_c can be determined experimentally by studying the relationship between C , T_1 and T_2 over a range of environmental conditions. It can also be estimated by calorimetry where an outcome of total heat transfer can be measured, and heat transfer by radiation and so on can be controlled or subtracted, leaving the convection component.

DIMENSIONLESS NUMBERS

It is often useful to be able to predict heat transfer by convection for objects of different sizes (e.g. from an adult to a child of similar shape) and in different fluids (e.g. from air to water). Heat transfer by convection will vary with the nature of the physical body tested (shape, orientation, size, etc.) as well as the fluid type, and effects can be predicted from their dimensions and properties. For this reason, dimensionless numbers of physical quantities have been created to allow the prediction of heat flow and heat transfer characteristics (and hence h_c) for groups of similar cases, particularly for bodies with similar shapes. They are useful in the prediction of heat flow and heat transfer

for similar cases but where the size or fluid type is changed. For example, if we know the heat flow around a heated cylinder in air, we can use the numbers to predict the heat flow for a smaller heated cylinder in water, or a larger heated cylinder in space, and so on. The dimensionless numbers are logical ratios of the characteristics of fluids which are made up of fundamental properties. These are presented in Tables 1.1 through 1.3.

A simple example of the principle of using the numbers is where size is different but shape is the same. One dimension, such as the diameter of a sphere, will determine all of the other characteristics of the sphere. For a person, arm length, standing height or leg length may be useful dimensions and any one of these is capable of predicting with acceptable accuracy the dimensions of all other body parts. So, for example, if we know the ratios of leg length between two people, we can estimate the ratio of all dimensions across the two people if they are of similar shape. The dimensionless numbers, however, require the use of more than a single dimension of shape alone. The flow of fluid around a solid body will depend on the *shape of the body*, the *velocity of fluid flow* and the *physical properties of the fluid*.

By analogy with shape as described above, where all of the dimensions can be determined from any one single dimension, so the velocity of fluid flow, for example, can be defined by the velocity at any appropriately defined point (e.g. environmental air velocity) when the flow pattern is the same. The pattern of fluid flow is determined by inertial and viscous forces. If the pattern of fluid flow around an object is to be similar, the ratios of those forces at corresponding points must be the same. The single number that is used to represent the pattern of fluid flow is the Reynolds number (Re), which is proportional to the ratio of the inertial forces to the viscous forces. It can be expressed as VL/ν , where ν is the kinematic viscosity of the fluid (μ/p), V its velocity and L the characteristic dimension describing the size of the object; p is the density of the fluid and μ its dynamic viscosity. The dimensions of

TABLE 1.1
Properties of Air at Sea Level

Temperature T (°C)	Dynamic Viscosity μ (N s m^{-2}) ($\times 10^{-5}$)	Density ρ (kg m^{-3})	Kinematic Viscosity ν ($\text{m}^2 \text{s}^{-1}$) ($\times 10^{-5}$)	Thermal Conductivity K ($\text{W m}^{-1} \text{K}^{-1}$) ($\times 10^{-2}$)
0	1.71	1.29	1.32	2.41
10	1.76	1.25	1.41	2.49
20	1.81	1.21	1.50	2.56
30	1.86	1.16	1.59	2.64
40	1.90	1.13	1.69	2.71
50	1.95	1.09	1.78	2.79
60	2.00	1.06	1.88	2.87
70	2.04	1.03	1.98	2.94
80	2.09	1.00	2.09	3.02

Source: Kerslake, D.M., *The Stress of Hot Environment*, Cambridge University Press, Cambridge, 1972.

Note: Heat capacity = $1000 \text{ J kg}^{-1} \text{ K}^{-1}$.

TABLE 1.2
Properties of Water

Temperature T (°C)	Dynamic Viscosity μ (N s m ⁻²) (× 10 ⁻⁵)	Density ρ (kg m ⁻³)	Kinematic Viscosity ν (m ² s ⁻¹) (× 10 ⁻⁸)	Thermal Conductivity K (W m ⁻¹ K ⁻¹) (× 10 ⁻²)	Specific Heat Capacity c (kJ kg ⁻¹ K ⁻¹)
0.01	179	1000	179	56.0	4.210
10	131	1000	131	58.1	4.193
20	100	998	100	60.0	4.183
30	80	995	80	61.7	4.179
40	65	992	66	63.2	4.179

Note: Density of ice at 0°C = 916.8 kg m⁻³.

these quantities are such that the Reynolds number is dimensionless. Its magnitude is arbitrary, since L can be any characteristic length defining shape. The important point is that if the Reynolds number is the same for two people or objects of similar shape but of different size, the pattern of fluid flow around them is similar, and this holds for fluids in general.

For forced convection, where external air velocity is dominant (e.g. wind), the Reynolds number can be used to describe the flow pattern. For heat exchange, the Nusselt number is used, which is proportional to the ratio of the actual coefficient of heat transfer by convection (h_c) to that by conduction (K) in the same fluid at rest ($Nu = h_c L / K$). For the thermal properties of fluids, the Prandtl number (Pr) is used, which is the ratio of the kinematic viscosity (μ/ρ) to the thermal diffusivity ($K/\rho c$): $Pr = \mu c / K$.

When a warm body is in still air, it heats the air around it, which reduces the density of the air. The air rises and the body loses heat by natural (free) convection. This will depend on the temperature difference between the surface and the air, the coefficient of expansion of the air and the gravitational field, as well as the properties involved in forced convection. The Grashof number is given by

$$Gr = \frac{agL^3(T_s - T_a)}{\nu^2} \quad (1.5)$$

where the terms are described in Table 1.3.

Santee and Gonzalez (1988) consider the use of dimensionless numbers to determine h_c for the human body. The Nusselt number is related to h_c by

$$h_c = \frac{NuK_f}{L} \text{ W m}^{-2} \text{ K}^{-1} \quad (1.6)$$

where K_f is the thermal conductivity of the fluid. For air (K_a):

$$K_a = 2.41 \times 10^{-2} + 7.8 \times 10^{-5} T_a \text{ W m}^{-1} \text{ K}^{-1} \quad (1.7)$$

TABLE 1.3
Physical Properties and Definitions

Property	Symbol	Units	Definition
Dynamic viscosity	μ	N s m^{-2}	Also known as absolute viscosity, it is the resistance of adjacent fluid layers to shear
Kinematic viscosity	ν	$\text{m}^2 \text{s}^{-1}$	Dynamic viscosity divided by density
Thermal conductivity	K	$\text{W m}^{-1} \text{K}^{-1}$	Property of a material to conduct heat
Specific heat capacity	c	$\text{kJ kg}^{-1} \text{K}^{-1}$	Heat required to raise 1 kg of material by 1 K. In the Prandtl number it is heat capacity per unit mass at constant pressure
Fluid velocity	V	m s^{-1}	Velocity of the fluid in which a body is immersed
Characteristic dimension	L	m	Dimension of an object which is chosen to represent its shape when using dimensionless numbers
Coefficient of expansion of air	a	K^{-1}	Represents expansion of air as it increases in temperature, for example, during convection ($a = 1/T$ where T is the absolute temperature)
Acceleration due to gravity	g	m s^{-2}	Acceleration due to the force of gravity ($g = 9.81 \text{ ms}^{-2}$ at sea level)
Reynolds number	Re	ND	A dimensionless number that specifies flow pattern. It is proportional to the ratio of inertial forces to viscous forces ($Re = VL/\nu$)
Nusselt number	Nu	ND	A dimensionless number that specifies heat exchange. It is proportional to the ratio of the heat transfer by convection to that by conduction in the same fluid at rest ($Nu = h_c L/K$)
Prandtl number	Pr	ND	A dimensionless number that connects momentum transfer with heat transfer. It is the ratio of the kinematic viscosity to the thermal diffusivity. It contains only the physical properties of the fluid so it is not affected by flow pattern ($Pr = \mu c/K$)
Grashof number	Gr	ND	A dimensionless number that combines factors related to heat transfer by natural convection. ($Gr = agL^3(T_s - T_f)/\nu^2$), where T_s is the surface temperature and T_f is the temperature of the fluid

For air, the Prandtl number is a constant (0.72) and the Grashof number can be calculated from Equation 1.5.

The kinematic viscosity of air (ν) is given by

$$\nu = 1.33 \times 10^{-5} + 9.0 \times 10^{-8} T_a$$

For natural (free) convection,

$$Nu = c' Gr^a \quad (\text{ND}) \tag{1.8}$$

where the empirical constants are determined by experiment for the shape of interest. An estimate for cylinders is $c' = 0.5$ and $a = 0.33$. Also, for natural convection an approximation including the Prandtl number is

$$Nu = 0.47(Gr Pr)^{0.25} \quad (1.9)$$

For forced convection,

$$Nu = B Re^n \quad (\text{ND}) \quad (1.10)$$

where B and n involve shape factors and, for a cylinder, can be estimated as $B = 0.24$ and $n = 0.60$.

The Reynolds number can be calculated from

$$Re = \frac{VL}{\nu} \quad (\text{ND}) \quad (1.11)$$

where V is the wind speed, the characteristic dimension (L) is determined by the actual dimensions (for a cylindrical representation of a standing person, the diameter is usually taken) and ν is the kinematic velocity of the fluid.

Santee and Gonzalez (1988) note that the original relationships presented above were derived from experiments in wind tunnels with laminar flow. For outdoors or when people are active, different relationships apply. Some variation may be accounted for if relative air velocity between the body and the air is used instead of environmental air velocity (walking speed when walking in still air, for example); however, differences can be significant and this questions the usefulness of the dimensionless number approach when assessing human thermal environments.

Kerslake (1972) notes that the method of using dimensionless numbers is powerful when predicting for conditions which are similar but the size of the body and the fluid are different. For applications in human thermal environments, people of different sizes often vary in shape. Most applications are for air at atmospheric pressure and, even for specific cases, experiments are difficult to conduct. Gonzales (1988) cites Gagge and Nishi (1983) who summarise that for natural (free) convection, h_c varies with temperature gradient, gravity (which is in the Grashof number) and density. For forced convection, h_c varies inversely with the characteristic dimension of the heated object (larger objects have lower h_c values). Barometric pressure affects density and hence h_c .

Values of h_c have been determined experimentally using calorimetry, and it is those values that are generally used in the rational assessment of human thermal environments (see Chapter 2). An example of the use of dimensionless numbers can be seen if we consider heat transfer for a person in air and in water.

CONVECTIVE HEAT TRANSFER IN AIR AND WATER

Heat transfer from the body to its surrounding environment is from core to skin and clothing surface and then between the surface and the environment. A major avenue for heat transfer is by convection, and this is the main mechanism for heat transfer

in water. Using dimensionless numbers it is possible to calculate the heat transfer coefficient in water from the basic properties of water and to compare this with the heat transfer coefficient in air. That is, for bodies of a similar shape but a different size.

When considering shapes of different sizes a characteristic dimension is needed and it is convenient to use the height of a person ($h=L$), although body volume, surface area or surface area to mass ratio may be even more useful when comparing heat transfer. Whichever is chosen, the dimension used should be consistent so that the numbers can be compared. For the present discussion, standing height will be taken as the characteristic dimension.

Consider a standing person, 1.8 m tall, in air at 20°C. The convective heat transfer coefficient is given by

$$h_c = \frac{NuK_f}{L} \quad (1.12)$$

where

Nu = Nusselt number

K_f = thermal conductivity of the fluid

L = the characteristic dimension (standing height = 1.8 m).

For air, K_a at 20°C is $2.56 \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1}$. For water, K_w at 20°C is $60 \times 10^{-2} \text{ W m}^{-1} \text{ K}^{-1}$.

For natural (free) convection in air, from Equation 1.9,

$$\begin{aligned} Nu &= 0.47(GrPr)^{0.25} \\ Gr &= \frac{agL^3(T_s - T_a)}{v^2} \\ &= \frac{0.00341 \times 9.81 \times 5.832 \times (33 - 20)}{(2.25 \times 10^{-10})} \\ &= 1.13 \times 10^{10} \\ Nu &= 0.47 \times (1.13 \times 10^{10} \times 0.72)^{0.25} \\ &= 140 \\ h_c &= \frac{Nu \times K_a}{L} \\ &= \frac{140 \times 2.56 \times 10^{-2}}{1.8} \\ &= 2.0 \text{ W m}^{-2} \text{ K}^{-1} \end{aligned}$$

For forced convection in air, Nu is estimated as

$$Nu = 0.24 Re^{0.6}$$

where the Reynolds number (Re) is given by VL/v .

For air at 20°C and velocity of 1.0 m s⁻¹:

$$Re = \frac{(1.0 \times 1.8)}{1.5 \times 10^{-5}}$$

$$= 1.2 \times 10^5$$

$$Nu = 0.24 \times (Re)^{0.6}$$

$$= 267.7$$

$$h_c = \frac{Nu \times K_a}{L}$$

$$= \frac{267.7 \times 2.56 \times 10^{-2}}{1.8}$$

$$= 3.81 \text{ W m}^{-2} \text{ K}^{-1}$$

h_c can be regarded as the larger value of those calculated for free or forced convection. So, as 3.81 (forced convection) is greater than 2.0 (free convection), $h_c = 3.81 \text{ W m}^2 \text{ K}^{-1}$, and for $T_s = 33^\circ\text{C}$ and $T_a = 20^\circ\text{C}$,

$$C = h_c (T_s - T_a)$$

$$= 50 \text{ W m}^{-2}$$

For natural (free) convection in water:

$$Nu = A(GrPr)^n$$

From Boutelier et al. (1977), $n = 0.275$, $A = 0.09$, so

$$Nu = 0.09(GrPr)^{0.275}$$

$$Gr = \frac{agL^3(T_s - T_a)}{v^2}$$

$$= \frac{\left(\frac{1}{293.15}\right) \times 9.81 \times (1.8)^3 \times (33 - 20)}{(10 \times 10^{-7})^2}$$

$$= 2.54 \times 10^{12}$$

$$Pr = \mu c / K$$

$$= \frac{(100 \times 10^{-5} \times 4183)}{(60 \times 10^{-2})}$$

$$= 6.971$$

$$Nu = 0.09 \times (2.54 \times 10^{12} \times 6.971)^{0.275}$$

$$= 396$$

$$h_c = \frac{Nu \times K_w}{L}$$

$$= \frac{396 \times 0.6}{1.8}$$

$$= 132 \text{ W m}^{-2} \text{ K}^{-1}$$

For forced convection in water at 20°C and velocity of 1.0 m s⁻¹: assume that $Nu = 0.24 \text{ Re}^{0.6}$, where the Reynolds number (Re) is given by VL/ν .

For water at 20°C and velocity of 1.0 m s⁻¹,

$$\text{Re} = \frac{(1.0 \times 1.8)}{10 \times 10^{-7}}$$

$$= 18 \times 10^5$$

$$Nu = 0.24 \times (18 \times 10^5)^{0.6}$$

$$= 1359$$

$$h_c = \frac{Nu \times K_w}{L}$$

$$= \frac{1359 \times 0.6}{1.8}$$

$$= 453 \text{ W m}^{-2} \text{ K}^{-1}$$

h_c can be regarded as the larger value of those calculated for free (natural) or forced convection, so, as 453 (forced) is greater than 132 (free), $h_c = 453 \text{ W m}^{-2} \text{ K}^{-1}$.

$$\begin{aligned} C &= h_c (T_s - T_a) \\ &= 5891 \text{ W m}^{-2} \end{aligned}$$

If we use the same equations as above but also change the size of the person or object then we can calculate h_c for children 1 m tall as opposed to adults 1.8 m tall, and so on. Table 1.4 provides estimates of values of the dimensionless numbers and a comparison of different h_c and consequent convective heat transfer values (C) for water and for air and for adults and children.

The dimensionless numbers for calculating heat transfer coefficients in water have been determined by a number of authors (Rapp, 1971; Breckenridge and Goldman, 1977). The values of h_c have also been determined by experiment.

Boutelier et al. (1977) investigated h_c values for 17 nude subjects at four water velocities (0, 0.05, 0.1 and 0.25 m s⁻¹) and a range of water temperatures from 33.7°C to 18°C. They found h_c values from 43 to 54 W m⁻² °C⁻¹ for still water and 272.9–497.1 W m⁻² °C⁻¹ for moving water, depending on the shivering rate. For cold water, the greater the shivering the larger the h_c value. These values were greater than the theoretical h_c values calculated by Rapp (1971), who found values of 94 W m⁻² °C⁻¹ for still water and 179–400 W m⁻² °C⁻¹ for water velocities from 0.1 to 0.5 m s⁻¹. An important finding from experimental studies is the identification of factors which have significant influence. These include different shapes for people as well as the effects of thermoregulatory responses such as vasoconstriction and shivering.

EVAPORATION

Evaporation is a change of state from liquid on a surface to vapour. The latent heat required is ‘taken’ from the surface, which is cooled. The vapour diffuses away from the surface in a manner similar to that in which heat diffuses in convection. The rate of mass transfer per unit area in this way is

$$m = h_D (C_{sk} - C_a) \quad (1.13)$$

where C_{sk} and C_a are the water vapour concentrations in the skin and in the air, respectively, and h_D is the mass transfer coefficient. The Sherwood number ($Sh = h_D L / D$) is analogous to the Nusselt number ($Nu = h_c L / K$), where D is the mass diffusivity. As with convection, the Reynolds number describes the flow pattern, but the Schmidt number ($N_{sc} = \nu / D$) replaces the Prandtl number (ν / α , where α is thermal diffusivity). For water vapour diffusing through air, D is almost equal to α . The Prandtl and Schmidt numbers are nearly equal, as are the Sherwood and Nusselt numbers. For that case, h_D and h_c are related by

$$h_D = \frac{h_c}{pc} \quad \text{so} \quad \frac{h_D}{h_c} = \text{const}$$

TABLE 1.4
Estimates of Dimensionless Numbers (Characteristic Dimension Standing Height) and Convective Heat Transfer for Adults and Children in Still and Moving Air and Water

Height (m)	2.0	1.8	1.6	1.4	1.2	1.0	0.8	0.6	0.4	0.2
Natural (Free) Convection in Air at 20°C ($Nu=0.47(GrPr)^{0.25}$, $Pr=0.72$)										
$Gr \times 10^7$	1547	1128	792	531	334	193	99	42	12	2
Nu	152	140	129	116	104	90	76	62	45	27
h_c ($W m^{-2} K^{-1}$)	2.0	2.0	2.1	2.1	2.2	2.3	2.4	2.6	2.9	3.5
C ($W m^{-2}$)	25	26	27	28	29	30	32	34	38	45
Forced Convection in Air at 20°C ($v=1.0 m s^{-1}$, $Nu=0.24(Re)^{0.6}$)										
$Re \times 10^3$	133	120	107	93	80	67	53	40	27	13
Nu	285	268	250	230	210	188	165	139	109	72
h_c ($W m^{-2} K^{-1}$)	3.7	3.8	4.0	4.2	4.5	4.8	5.3	5.9	6.9	9.2
C ($W m^{-2}$)	48	50	52	55	58	63	68	77	90	119
Natural (Free) Convection in Water at 20°C ($Nu=0.09(GrPr)^{0.275}$, $Pr=6.97$)										
$Gr \times 10^{10}$	348	254	178	119	75	44	22	9	3	0.3
Nu	432	396	359	322	283	244	203	160	114	65
h_c ($W m^{-2} K^{-1}$)	129	132	135	138	142	146	152	160	172	194
C ($W m^{-2}$)	1683	1714	1750	1792	1841	1900	1976	2078	2230	2519
Forced Convection in Water at 20°C ($v=1.0 m s^{-1}$, $Nu=0.24(Re)^{0.6}$)										
$Re \times 10^3$	2000	1800	1600	1400	1200	1000	800	600	400	200
Nu	1448	1359	1267	1169	1066	955	836	703	551	363
h_c ($W m^{-2} K^{-1}$)	434	453	475	501	533	573	627	703	827	1091
C ($W m^{-2}$)	5648	5891	6175	6514	6928	7452	8148	9142	10752	14187

- Notes:*
1. Where both natural (free) and forced convection occur together with an h_c value for each condition, the h_c value often used in the calculation of heat transfer is the greater of the two values.
 2. People vary in shape and size and are not static. Heat transfer is complex and the values provided above are approximations that demonstrate the principle of using dimensionless numbers.
 3. A comfortable skin temperature at a constant value of 33°C is assumed. In practice, this will vary with human thermoregulation.

This is the Lewis rule (Lewis, 1922); it applies to all wind speeds and is used to relate convective and evaporative heat transfer (see Kerslake, 1972; Monteith and Unsworth, 1990).

In an analysis of human thermal environments, it is usual to replace mass concentrations with vapour pressures and to express evaporative heat transfer as

$$E = h_e (P_{sk,s} - P_a) \quad (1.14)$$

where $P_{sk,s}$ is the saturated vapour pressure at skin temperature and P_a is the partial vapour pressure in the air. The Lewis relation is then

$$\frac{h_e}{h_c} = LR$$

where LR is the Lewis relationship and is a constant ($LR = 16.5 \text{ K kPa}^{-1}$).

So, if we know h_c we can estimate h_e from

$$h_e = 16.5h_c \quad \text{W m}^{-2} \text{ kPa}^{-1} \quad (1.15)$$

and we can calculate heat transfer by evaporation from Equation 1.14.

RADIATION

Radiation is part of the electromagnetic spectrum (Figure 1.1); when absorbed (by a surface), radiation with wavelengths from visible light to radio waves provides heat. All bodies above a temperature of absolute zero emit and absorb radiation. Radiation is usually composed of a spectrum of wavelengths rather than an individual wavelength, and the peak wavelength in the spectrum depends on temperature. As the temperature rises, so the peak energy of the radiation spectrum for a body decreases in wavelength. When assessing human thermal environments, two categories of radiation are considered. These are solar radiation, which is of short wavelength ranging from ultraviolet to the near infrared, and radiation from surrounding surfaces up to about 100°C in the far infrared. Radiation can transfer across a vacuum (e.g. through space from the sun), and heat transfer between two bodies is driven by the difference in the fourth powers of the absolute temperatures.

Heat transfer by radiation is given by

$$R = h_r (T_1^4 - T_2^4) \quad \text{W m}^{-2} \quad (1.16)$$

where h_r is the radiative heat transfer coefficient and $(T_1^4 - T_2^4)$ is the difference in the fourth power of the absolute temperatures of the interacting surfaces.

A fuller description of radiant temperatures and the calculation of radiation heat transfer for the human body are provided later in this chapter and in Chapter 2.

BASIC PARAMETERS

TEMPERATURE

At a molecular level, temperature can be considered as the average kinetic energy (heat) in a body. For a given state (solid, liquid or gas), if heat energy is lost from a body its temperature will fall, and if it flows into a body its temperature will rise. From the second law of thermodynamics there will be a net energy flow from

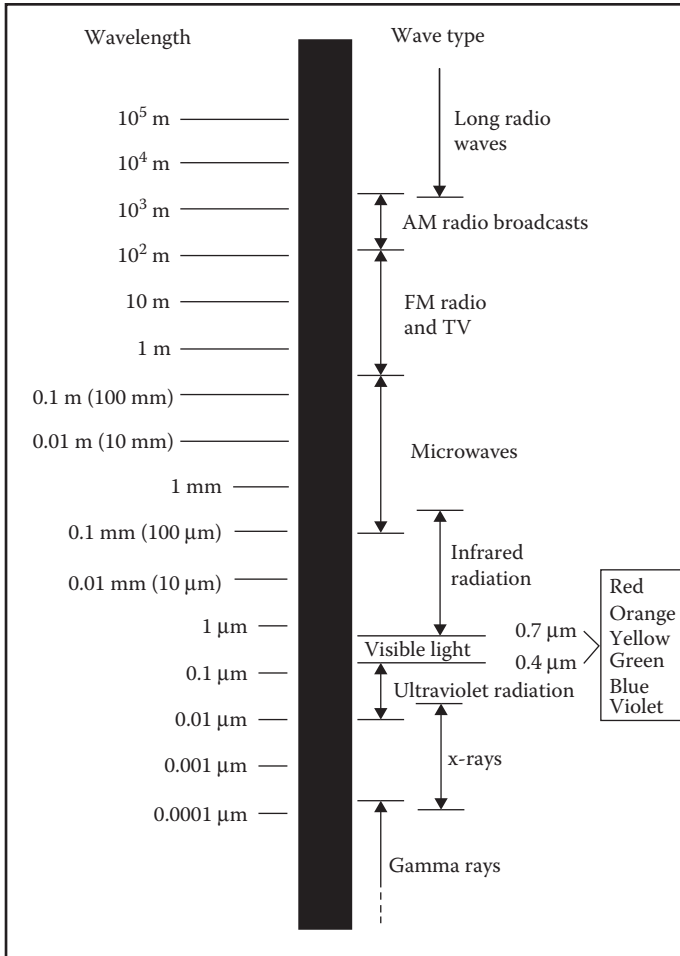


FIGURE 1.1 The electromagnetic spectrum.

bodies at higher temperatures to bodies at lower temperatures. The temperature of the human body is an important indicator of its condition (comfort, heat or cold stress, ability to perform tasks). Humans are homeotherms and ‘attempt’ to maintain their internal body temperature near to about 37°C. A deviation of more than a few degrees from this value can have serious consequences. The temperature of the human body will therefore be greatly affected by the temperature of fluids or solids surrounding it, as these will influence the heat transfer to and from the body. The human body is commonly surrounded by clothing and then almost entirely by air. Contact may also be with solid surfaces, water (total or partial immersion), other fluids or even space. The thermodynamic principles of heat transfer will apply in all of these cases. Throughout this book, the ‘normal’ case of a person in air is assumed unless otherwise stated. A ‘driving force’ for heat transfer between the human body and the surrounding air will therefore be determined by air temperature.

AIR TEMPERATURE (t_a)

For practical convenience, air temperature can be defined as ‘the temperature of the air surrounding the human body which is representative of that aspect of the surroundings which determines heat flow between the human body and the air’. Naturally, the temperature of the air will vary; heat exchange between bodies is a continuous process. The temperature of the air at a great distance from the human body of interest will not necessarily be representative of that which determines heat flow. The temperature of the air very close to the (clothed) body will also not be representative as this will be influenced by so-called boundary conditions; for example, in a ‘cold’ environment there will be a layer of ‘warmer’ air surrounding the body.

RADIANT TEMPERATURE

In addition to the influence of air temperature on the temperature of the human body there is also the influence of radiant temperature. Heat is exchanged by radiation between all bodies, and there is a net heat flow from a hot to a cooler body by an amount related to the difference between the fourth powers of the absolute temperatures of the two bodies. There is a net flow of radiant energy between the sun and the earth (i.e. no intervening medium is required – it will flow through a vacuum). Thermal radiation is part of the electromagnetic spectrum that includes x-rays (short wavelength), light and radio waves (long wavelength). A useful way (although the analogy should not be taken too far) of conceptualising thermal radiation is therefore to relate it to light. In any environment there will be continuous energy exchanges, reflections, absorptions and so on. As a person moves around a room, the lighting environment (and thermal radiation) may change. At any point in space, therefore, there is a unique radiation environment.

McIntyre (1980) describes the concept of the radiation field. At any point in a radiation field there will be a dynamic exchange (e.g. in time and direction) of energy (heat) by radiation. The overall radiation field, in a room for example, can be defined in terms of heat transfer or, more conveniently, in terms of radiant temperatures. In the assessment of humans in thermal environments it is the radiation exchange, at the position of the person in the radiation field, that is important. This can be analysed to increasing levels of complexity. For convenience, radiant temperatures are used, which are defined by McIntyre (1980) as ‘the temperature of a black body source that would give the same value of some measured quantity of the radiation field as exists in reality’. Two radiant temperatures are commonly used to summarise the radiant heat exchange between the human body and the environment: the *mean radiant temperature*, which provides an overall average value, and the *plane radiant temperature*, which provides information concerning direction of radiant exchange (and if measured in different directions can give variations in direction about the mean radiant temperature). Plane radiant temperature will be important, for example, where relatively large radiant ‘sources’ are present in an environment at a specific orientation to the body (e.g. electric fires, steel furnace, heated ceiling, the sun or a very cold wall).

Mean Radiant Temperature (t_r)

The mean radiant temperature is defined as ‘the temperature of a uniform enclosure with which a small black sphere at the test point would have the same radiation exchange as it does with the real environment’. The use of the sphere in the definition shows the average in three dimensions. The reference to an equivalent effect in the defined standard environment is a widely used technique. The definition above is generally used and is consistent with the concept of the radiation field. For a sphere, the mean radiant temperature will not depend on its orientation in the surroundings. For a nonspheroidal shape such as the human body, the concept of the *effective mean radiant temperature* is used: ‘the temperature of a uniform enclosure with which the test surface would have the same radiation exchange as it does with the real environment’. This will depend on the orientation of the object in the surroundings.

There has been some inconsistency in defining mean radiant temperature. ISO 7726 (1998), for example, gives the definition: ‘The mean radiant temperature is the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non uniform enclosure’. This standard, and other references (e.g. Fanger, 1970), define mean radiant temperature directly with respect to the human body. The use of a sphere is therefore regarded as an approximation to the mean radiant temperature (still given the symbol t_r). The use of an ellipsoid or cylindrical sensor is then said to be superior as it represents the shape of a standing person more closely than a sphere. The mean radiant temperature will thus depend on the orientation of the human body in the radiation environment.

The mean radiant temperature for the human body can be calculated from the temperature of surrounding surfaces and their orientation with respect to the body. The methods of measurement, analysis and calculation are described in Chapter 5.

Plane Radiant Temperature (t_{pr})

ISO 7726 (1998) defines the plane radiant temperature as ‘the uniform temperature of an enclosure where the radiance on one side of a small plane element is the same as in the non-uniform actual environment’. McIntyre (1980) defines the plane radiant temperature at a point as ‘the temperature of a uniform black hemisphere, centred on a plane element with its basal plane in the plane of the element which would give the same irradiance on the element’. (He defines irradiance as the flux per unit area falling on a surface from all directions.) The point is that the plane radiant temperature is related to radiant exchange in one direction. Both definitions refer to a small plane element at a point. The confusion between definitions relating to either a point or to the human body does not seem to apply. However, the effects of directional radiation will clearly be influenced by the orientation of the body.

The plane radiant temperature can be measured in many orientations: for example, up/down, left/right and front/back. It can also be measured in the direction of a radiation source such as the sun. The projected area factor is estimated as A_p/A_r , where A_p is the surface area projected in one direction and A_r is the total radiant surface area. For example, for a standing man, the up/down projected area factor is low (0.08). It is higher for left/right orientation (e.g. 0.23) and higher again for front/back

(e.g. 0.35). If one could imagine the plane radiant temperature measured on the six faces of a cube, then ISO 7726 (1998) gives the following equation as an estimate of the mean radiant temperature for a standing man:

$$t_r = \frac{0.08(t_{pr1} + t_{pr2}) + 0.23(t_{pr3} + t_{pr4}) + 0.35(t_{pr5} + t_{pr6})}{2(0.08 + 0.23 + 0.35)} \tag{1.17}$$

where t_{pr1} to t_{pr6} are the plane radiant temperatures in directions (1) up, (2) down, (3) right, (4) left, (5) front and (6) back.

This point can also be shown (and values estimated) using photographic techniques (e.g. Fanger, 1970; Underwood and Ward, 1966; see Figure 1.2). To avoid possible confusion, the reader should distinguish between A_p/A_r , the projected area factor in one direction and A_r/A_D , the effective radiation area factor, since the latter is the ratio of the total area of the body ‘available’ for radiant exchange divided by the total surface area of the body (A_D ; see Chapter 2). It will depend on posture. ISO 7933 (1989) gives a value for A_r/A_D of 0.77 for a standing person, 0.72 sitting and 0.67 crouched. Clearly, the integration of projected area factors over all directions gives

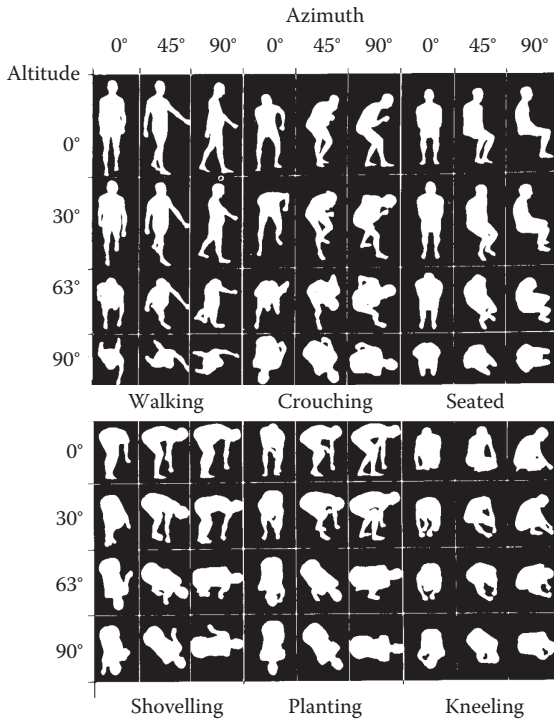


FIGURE 1.2 A section of silhouettes of a subject in various postures, corresponding to the areas illuminated by the sun’s rays at the angles of altitude and azimuth shown. (Adapted from Underwood, C.R. and Ward, E.J., *Ergonomics*, 10, 399–410, 1966.)

A_r . Radiant temperatures are further discussed in Chapter 2, in relation to radiant heat transfer.

SOLAR RADIATION

The principles in the use of radiant temperatures apply equally for indoor and outdoor environments. However, the particular nature of solar radiation in terms of its quality (spectral content), intensity and directional properties requires it to be given special consideration. Radiant heat is part of the electromagnetic spectrum (see Figure 1.1).

Any effects of radiation intensity may be due to both the level of radiation and its wavelength or spectral content. It will also depend on the direction of the radiation received by the body and the body posture and orientation.

Quantity: Solar Radiation Level

At the mean distance of the earth from the sun, that is, 1.5×10^{11} m, the irradiance of a surface normal to the solar beam is known as the *solar constant*. Satellite measurements provide a value of 1373 W m^{-2} for the solar constant. Direct solar radiation at the ground, however, has a maximum value of about 1000 W m^{-2} as some heat is scattered and absorbed by the atmosphere. This is further absorbed by cloud cover, aerosols, pollution and so forth (see Figure 1.3).

Quality: Spectral Content of Solar Radiation

The total energy emitted by the sun (E) is obtained by multiplying the solar constant by the area of a sphere at the earth’s mean distance d :

$$E = 4\pi d^2 \times 1373 = 3.88 \times 10^{26} \text{ W} \tag{1.18}$$

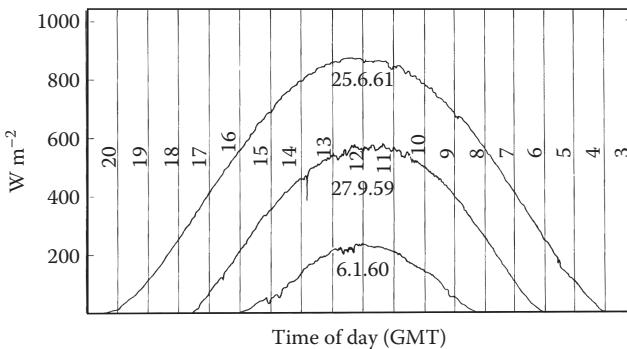


FIGURE 1.3 Solar radiation on three cloudless days at Rothamsted, UK (52°N , 0°W). During the middle of the day, the record tends to fluctuate more than in the morning and evening, suggesting a diurnal change in the amount of dust in the lower atmosphere, at least in summer and autumn. Three recorder charts were superimposed to facilitate this comparison. (Adapted from Monteith, J.L. and Unsworth, M.H., *Principles of Environmental Physics*, 2nd edn, Edward Arnold, London, 1990.)

For black-body radiation the energy emitted obeys Stefan's law, ($E = \sigma T^4$), so:

$$\sigma T^4 = 3.88 \times \frac{10^{26}}{4\pi r^2} \quad (1.19)$$

The radius of the sun $r = 6.69 \times 10^8$ m, and the Stefan–Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ ($\text{W m}^{-2} \text{K}^{-4}$), so from Equation 1.19 the temperature of the sun $T = 5770$ K (Monteith and Unsworth, 1990).

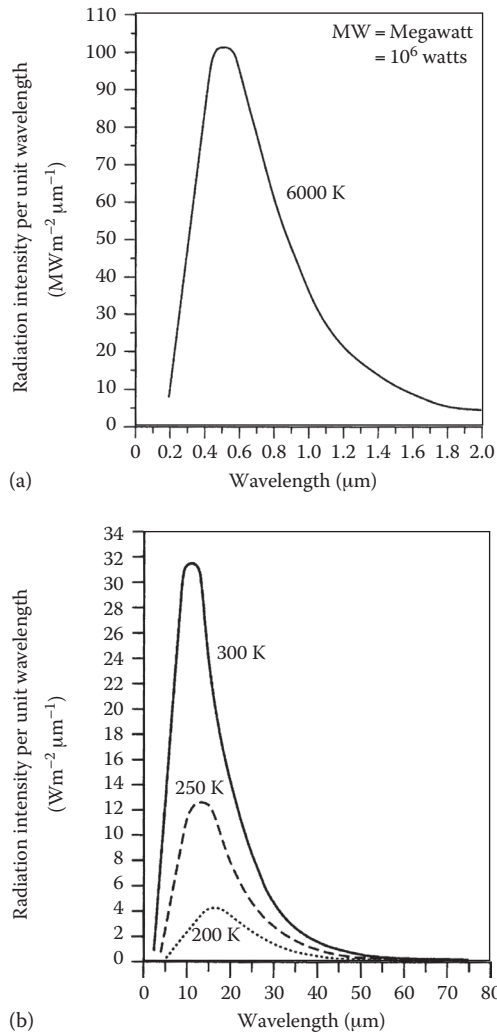


FIGURE 1.4 Variation in the intensity of black-body radiation with wavelength. (a) $T=6000$ K (approximately the emission temperature of the sun). (b) $T=200$ K, 250 K and 300 K (range of earth emission temperatures). Note the differences in scale. (Adapted from Neiburger, M., Endinger, J.G. and Bonner, W.G., *Understanding Our Atmospheric Environment*, W.H. Freeman, San Francisco, 1982.)

The higher the surface temperature of an object is, the shorter the wavelength of radiation that will be emitted (Wien’s law). The solar spectrum therefore has radiation at much shorter wavelengths than terrestrial emission, where temperatures are much lower than those of the sun (see Figure 1.4). Note that the ultraviolet spectrum can be subdivided into ultraviolet A (UVA: 400–320 nm), which produces tanning in the sun, ultraviolet B (UVB: 320–290 nm), which is responsible for skin cancer and vitamin D synthesis, and ultraviolet C (UVC: 290–200 nm), which is potentially harmful but is absorbed by ozone in the stratosphere (see Table 1.5).

Solar Radiation and the Human Body

Santee and Gonzalez (1988) identify six radiation terms that are relevant to the thermal responses of the human body. There are three solar radiation terms – *direct*, *diffuse* (scattered sky) and *reflected* (solar from the ground) – two thermal radiation terms (*sky* and *ground*) and the thermal radiation emitted from a person (see Figure 1.5). A commonly used term is the *albedo*, which is the amount of radiation reflected from a surface. It is calculated by dividing the amount reflected by the total amount arriving at a surface.

Direct Solar Radiation

Direct solar radiation arrives from the direction of the solar disc. This varies throughout the day and year due to the earth’s rotation on its own axis and its orbit around the sun. With respect to the human body, it will also depend on the body’s orientation and posture. Although direct solar radiation falls across the entire body surface area that is exposed to direct sunlight, the amount of direct solar radiation received is equal to the full radiative intensity normal to the solar beam multiplied by the cross-sectional area of an object normal to the solar rays (A_p). This relationship is known as Lambert’s cosine law. Note that A_p values are normal to the direction of the sun. These can be seen in Figure 1.2. Underwood and Ward (1966) give the following equation for A_p for an average man:

$$A_p = 0.043 \sin \theta_s + 2.997 \cos \theta_s \sqrt{(0.02133 \cos^2 \phi + 0.0091 \sin^2 \phi)} \text{ m}^2 \quad (1.20)$$

TABLE 1.5
Distribution of Energy in the
Spectrum of Radiation Emitted by
the Sun

Waveband (nm)	Energy (%)
0–300	1.2
300–400 (ultraviolet)	7.8
400–700 (visible/PAR ^a)	39.8
700–1500 (near infrared)	38.8
1500–∞	12.4
	100.0

^a Photosynthetically active radiation.

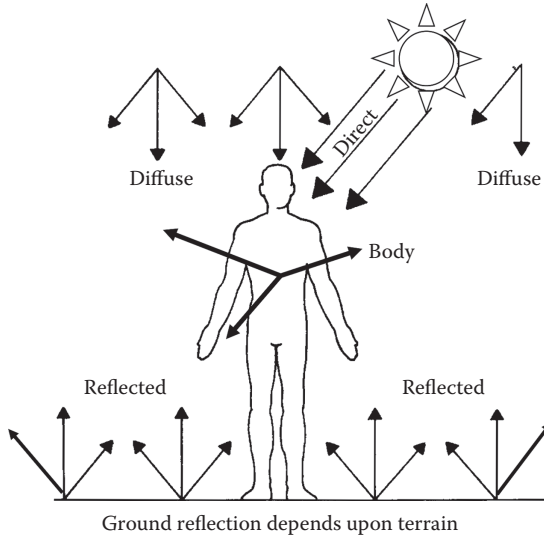


FIGURE 1.5 The impact of direct, diffuse and reflected solar radiation is dependent on the orientation of the individual relative to the radiation source. (Adapted from Pandolf, K.B., Sawka, M.N. and Gonzalez, R.R., *Human Performance Physiology and Environmental Medicine at Terrestrial Extremes*, Brown and Benchmark, USA, 1988.)

where:

- θ_s = solar elevation angle = angle between the sun and the horizon (note that the complementary angle to θ_s is θ_z = zenith angle = deviation of the sun from vertical)
- ϕ = azimuth angle = orientation of the body relative to the sun: $\phi = 0$ = facing directly towards or away from the sun; $\phi = 90$ = sideways (shoulders towards the sun) (see Santee and Gonzalez, 1988)

Diffuse Solar Radiation

Diffuse solar radiation describes all other (than direct) scattered radiation received from a blue sky (including the very bright aureole surrounding the sun) and from clouds, either by reflection or transmission (Monteith and Unsworth, 1990).

Diffuse solar, reflected solar, ground thermal and sky thermal radiation are considered as isotropic, that is the radiation is emitted in all directions from an area source. For a fuller description of solar radiation, the reader is referred to Monteith and Unsworth (1990). A description of how to measure solar radiation is provided in Chapter 5.

TEMPERATURE CHARTS AND SCALES

Temperature refers to how hot or cold an object or fluid is. It is related to heat content (i.e. temperature as average kinetic energy); however, temperature will also depend on properties such as specific heat capacity and mass. The thermal sensations of hot or cold are psychological phenomena and, although there are physiological mechanisms in the body which respond to temperature, thermal sensation depends on such

things as previous experience, individual differences and rates of change of temperature. Humans are therefore not good instruments for measuring temperature and cannot provide reliable temperature scales.

If there is no net heat flow between two objects in contact, then they are at the same temperature. The steady-state level of mercury in a glass thermometer placed in melting ice is the state of the mercury at the same temperature as melting ice. The state of the mercury in boiling water is its state at the temperature of boiling water. This provides the basis of thermometry and temperature measurement scales.

The origins of scales for quantifying temperature and temperature changes derive from human applications. In the early seventeenth century, Sanctorius (see Cetas, 1985) developed an air thermometer and used it to measure oral and hand skin temperatures. There are now three temperature scales in common use: the practical working scales of Celsius (sometimes called centigrade) and Fahrenheit, and the theoretical absolute temperature (Kelvin) scale.

Practical Working Scales (°C, °F)

Working scales of temperature are defined by assigning arbitrary values (e.g. 0 and 100) to the temperature of a reproducible known event (e.g. freezing or boiling). The Celsius (°C) and Fahrenheit (°F) scales use two points. The temperature of the freezing point of water is given the value 0°C and 32°F. The temperature of the boiling point of water is given the value 100°C and 212°F (at 1 atm pressure). The Celsius scale is divided into 100 equal divisions or degrees (1°C difference) and the Fahrenheit scale into 180 equal divisions (1°F difference). A simple method of converting from one to the other is by equating the 180°F to 100°C temperature difference. Therefore, for temperature difference $180F = 100C$, so:

$$F = \frac{9}{5}C \quad \text{or} \quad C = \frac{5}{9}F$$

temperature difference, and as 0°C = 32°F the scale values convert using

$$F = \frac{9}{5}C + 32 \quad \text{or} \quad C = \frac{5}{9}(F - 32)$$

For example, a body temperature of 98.4°F gives

$$\begin{aligned} C &= \frac{5}{9}(98.4 - 32) \\ &= 36.9^\circ\text{C} \end{aligned}$$

A body temperature of 37°C gives

$$\begin{aligned} F &= \frac{9}{5} \times 37 + 32 \\ &= 98.6^\circ\text{F} \end{aligned}$$

The Celsius scale is the most widely used throughout the world and is an SI unit; however, the Fahrenheit scale is still used, for example, in the United States.